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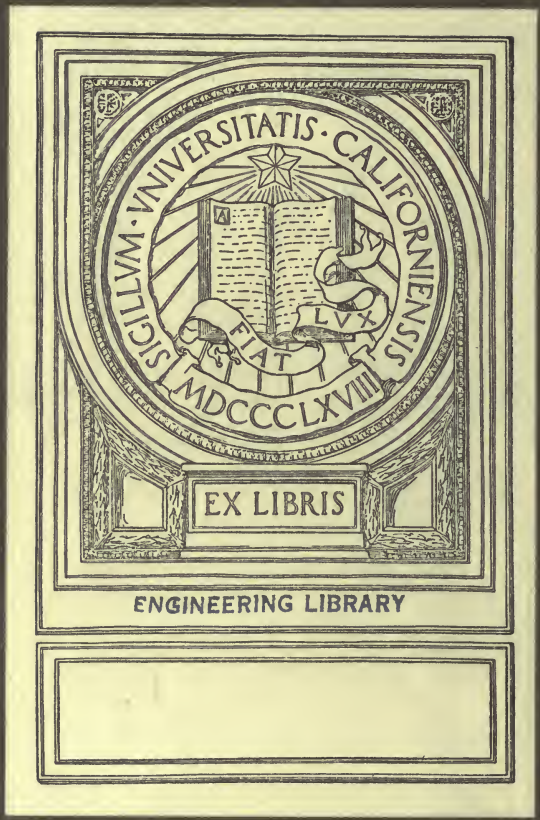
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WATER WHEELS OF IMPULSE TYPE.

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INTRODUCTORY.

The modern development of this type of hydraulic prime-mover dates back to the "hurdy-gurdy" water wheel constructed by the early gold miners of California. The history of the wheel will be found in Volume 29, 1899, Transactions of The American Institute of Mining Engineers, Page 852,—"The Tangential Water Wheel".

The wheel has been designated by several different names, viz; "Impulse", "Impulse-reaction", "Free-jet", "Spoon-wheel", "Tangential" and "Pelton", but in view of the fact that Pelton developed the characteristic dividing wedge of the buckets, and was the first to develop the wheel from the commercial standpoint, the engineering world has adopted the name "Pelton Wheel" as being synonymous of the type, as it is a distinct type of hydraulic prime-mover, differing radically in principle from the pressure types and the various forms of partial turbines developed in Europe and in the eastern part of the United States.

EARLY DEVELOPMENT.

In considering its development from 1850 to 1915, it will be best to divide this time into two periods. First, the "Mining Period", running from 1850 to 1890, during which time the wheel was developed primarily by the miners, and its principal use was in connection with the mining industry. Its design and development were restricted in merit and quality by the rather

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crude requirements of the mining industry, and, of course, refinements in design and construction beyond the requirements of that industry were not justified. The power of each wheel was also limited to comparatively small horsepower output, as the nature of the driven apparatus was such that there was no call for large power output from a single wheel. During this period the effective head or pressure was comparatively low, averaging from 200 to 500 feet. The power developed by the wheels was necessarily used where it was developed, the length of the transmission being limited to that feasible for a shaft, belt, or rope drive.

Second, the "Electrical Period", running from 1890 to date, during which period, radically new and severe requirements were demanded from the makers of the wheel. The size and power output were no longer limited to the requirements of the immediate location of the wheel, but only by the amount of power that could be developed by the water available. The working head was greatly increased, as new conditions justified greater expenditures in the development of the water shed, with its storage dams, conduits, regulating reservoirs and penstocks. The problem of successful speed regulation to meet the requirement of operating two or more dynamos in synchronism, or two or more widely separated power plants on the same system of transmission and distribution also arose, and involved the necessity of a governing means sufficiently sensitive, accurate and rapid to maintain a uniform speed with instantaneous changes of power demand from zero load to full load and inversely, and with frequent large percentages of the total capacity of the water wheel instantly rejected or applied.

During this period, a further requirement developed, viz., continuous service; whereas, before this period, continuous service, and all that it means, was an unknown quantity. Long distance transmission, reaching out over wide territories and supplying power and light to many commercial industries, towns and cities, gave an entirely new meaning to the term continuous service, and demanded apparatus of the highest type of engineering design, material and workmanship, to meet its necessities.

In the mining age, the problem of speed regulation was very

simple, since the early use of such wheels was principally to drive stamp mills, saw mills, etc., where the power output was quite constant and the friction load on the shafting and driven machinery formed a large proportion of the power developed. In such cases regulation was accomplished usually by partially closing the gate valve placed back of the nozzle entrance, or as a refinement, in wheels using a rectangular slot nozzle, a sliding tongue was inserted in the orifice, that could partially or fully open the orifice. A refinement for wheels using a circular jet was the adoption of the deflecting nozzle, to permit of projecting the entire jet against the buckets of the wheel, or partially or wholly deflecting the jet outside the path of the buckets. Other improvements were made, such as in using cast iron instead of wood, etc.; but, in general, it is reasonable to state that the impulse or Pelton wheel of the Mining Period was comparatively crude in its engineering design and in its construction, though suitable for the work it was called upon to do. Many of these early wheels are still in use, and they were of great service to mankind.

During the Electrical Age the development of the wheel by modern engineering methods, such as were in vogue in other types of prime-movers, dates back to the first work in long-distance electric transmission, made possible by the invention and development of the static transformer. This would start the consideration of this later development with the years 1890-1893 with the installation of the Telluride Power Company's Plant, the justly celebrated Pomona Plant, and the plant of the Redlands Electric Light & Power Co. The progress in the art from that time has gone hand in hand with a similar development in the co-related work of the electrical engineer. Thus the hydro-electric prime-mover has brought about a great and rapid development in the water wheel, with its accessories, as it has in the development of the dynamo. A similar development has also taken place in steam-electric prime-movers. New problems in the designing of both types of prime-movers—particularly those connected with safety, reliability and accurate regulation—have thus been brought about by the special requirements of the electric dynamo, with the co-related problems introduced by the require-

ments of long-distance transmission, continuous service, and speed regulation of a character heretofore unknown, in combination with the demand for prime-movers of much greater power output, high rotative speed, and to operate under extremely high heads and therefore high water pressures.

Tracing the development from 1890-1893: the Telluride, Pomona, Redlands, and the other early hydro-electric plants quickly demonstrated that the wheel so successful in the Mining Period was entirely inadequate in its design, material and workmanship to meet the more severe requirements of the hydro-electric generating units.

During the period from 1890 to date, there has been a constant development to satisfy the more and more severe and exacting demands of the rapidly growing industry.

To establish a comparison: in the plant of the Telluride Power Company at Ames, Colorado, installed in 1890, were two hydro-electric single-phase units, each of 150 kw. output, consisting of a Pelton wheel directly connected to a Westinghouse generator. These wheels operated under a head of 500 ft. (152 m.).

In the Pomona Plant of the San Antonio Light & Power Co., Pomona, California, installed in 1891, were two hydro-electric single-phase units, each of 120 kw. output, consisting of a Pelton wheel operating under a head of 402 ft. (122 m.) and directly connected to a Westinghouse generator.

In the Mill Creek Power House No. 1 of the Redlands Electric Light & Power Co., near Redlands, California, installed in June 1892 and first put into operation on September 7, 1893, were two hydro-electric three-phase units, each of 250 kw. output, consisting of a Pelton wheel operating under a head of 295 ft. (90 m.) and directly connected to a General Electric generator. These were the first three-phase generators made in the United States, and this was the first three-phase transmission system to be put into service in the United States.

The development since these early installations has been very remarkable, as will be appreciated in completing the comparison with the more recent developments: there are five or more power plants in the United States where the wheels operate

under heads of approximately 2000 ft. (610 m.) and over, and in Europe one plant operating under a head of 2890 ft. (880 m.), and one plant recently completed operating under a head of 5250 ft. (1720 m.), wherein a single jet of water 1½ inches diameter develops 3000 horsepower. The increase in the size of the units is more striking, starting with the 150-kw. units at Ames in 1890 to the recent generators of 12,500 kw. output and driven by Pelton wheels of 20,000 hp. capacity. To fully appreciate this development, it is necessary to consider that it is the result of only twenty-five years' work, which period covers the entire history of the art of Hydro-Electric Power Generation and Transmission.

The details of design of each hydraulic prime-mover are controlled and determined by the natural conditions existing at the location where it is to be installed, and under which it is to operate. These natural conditions and limitations differ over a wide range with every installation; therefore, the hydraulic prime-mover cannot be standardized in design, as is possible with electric generators, steam engines, or steam turbines, but each prime-mover must be specially designed and developed.

The principal controlling factors of the design are: (1) The water quantity curve, or the quantity of water available during each period of each day and throughout the year; (2) the total head that it is possible or profitable to develop; (3) the presence of satisfactory sites, favorably located, on which to construct storage reservoirs, or equalizing reservoirs, from which the pressure pipes will carry the water to the wheels; (4) the character of the load curve that is to be carried; (5) the most economic speed of rotation of the electric generator or driven machinery; (6) whether or not riparian or irrigators' rights have a controlling interest that will affect the possibilities of water storage during the sag in the daily load curve, so as to permit the water not required during this sag in the load curve to be conserved and available to carry the peaks of the load curve. These conditions primarily determine the general type and capacity of the installation, the number and capacity of the separate units into which the plant will be subdivided, the speed of rotation, the method of speed regulation and whether or not water economizing meth-

ods can be used to an advantage. These controlling factors differ so materially in each installation that they not only affect the general type or arrangement of the design but also the details.

The general type of unit to be adopted in a given power plant will, therefore, be determined by the particular arrangement and characteristics of details to be incorporated in the unit, as required to meet the conditions under which the prime-mover is to operate; it being appreciated that there are in practically every prime-mover certain similar details, differing only in size and mode of operation.

WHEEL RUNNERS AND BUCKETS.

The term "wheel runner" contemplates the entire wheel proper, consisting of some form of center, to the rim of which the buckets are attached. There are two general types of wheel construction: First, the Double-lug buckets; secondly, the Chain-type or Triple-lug bucket.

The double-lug bucket is arranged with two lugs cast integral with the bucket. The wheel center consists of a single rim. The two lugs of the bucket are accurately machined to a press fit over the rim of the wheel center and the buckets are held in position on the rim of the wheel center by two bolts, which are pressed into reamed holes passing through the two lugs of the bucket and the rim of the wheel center, thus making a very substantial construction. This type of wheel is shown in Fig 1 and the photograph of the De Sabla buckets (Fig. 2).

The wheel illustrated in Fig. 1 is operating under 865 ft. (264 m.) head, at 225 revolutions, and develops 3750 horsepower. This wheel is constructed with a forged steel disc, which is carried on a cast-steel hub with follower plate.

One of the four wheels installed in the Mill Creek No. 3 plant of the Southern California Edison Company furnishes an interesting illustration of the double-lug type of bucket. This wheel operates under 1900 ft. (580 m.) head at 430 revolutions per minute, developing 1600 horsepower, and has been in continuous service since March 17, 1903. This wheel held the record for some time as operating under the highest head of any wheel in the world. The wheel center consists of an annealed open-hearth

Fig. 1. Wheel of Double Lug Construction, Puget Sound Power Company. Wheel center made from steel forging bolted to a wheel hub with follower plate. Develops 3750 hp. under 865 ft. (264 m.) effective head, at 225 r.p.m.

steel casting, the buckets being of special hard bronze. This type of construction is thoroughly satisfactory for all installations where the ratio between the diameter of the jet and the pitch diameter of the wheel is favorable. In this type there are two bolts for each bucket, and where, owing to the large ratio be-

tween the pitch diameter of the wheel and the diameter of the jet, there is ample room for the two bucket bolts and proper lugs on the buckets, this type of construction is thoroughly satisfactory.

The photograph of the De Sabla wheel (Fig. 2) also shows buckets of the double-lug type of construction. This photograph is of particular interest, as it shows the condition of the buckets as they were on February 25, 1915, the wheel having gone into service October 22, 1903, and having been in almost continuous service since that time with practically no expense whatever for maintenance. The construction of this wheel shows a forged nickel-steel disc 4 inches thick at the rim and 10 ft. 4 in. in diameter. This forged wheel-center is then bolted directly to a flange forged solid with the hollow nickel-steel wheel shaft. The buckets are made of high-carbon open-hearth steel castings. This record will be of particular interest to engineers as showing what can be accomplished in the way of durability and continuity of service from a properly designed "Pelton" wheel. These wheels operate under 1531 ft. (467 m.) head at 240 revolutions per minute and develop 3700 horsepower.

The chain type of construction differs materially from that of the double-lug construction. In the chain-type construction a double rim is required. This is sometimes made of a wheel with a "U"-type rim. Generally, however, it consists of two separate wheel centers, the hubs being so finished as to bring the space between the rims of the two wheels a proper distance apart. The bucket is provided with three lugs, a forward center lug and two rear lugs. Figure 3 shows clearly the arrangements of the lugs of the bucket. Figure 4 shows the assembled wheel runner complete. These wheels operate under 1330 ft. (405 m.) head at 360 revolutions per minute, and each wheel develops 20,000 horsepower.

In this design the center or forward lug of the bucket is a close fit between the two rims forming the duplex wheel center. The two rear lugs of the bucket straddle the rims of the wheel center, the spacing of the lugs of the bucket and the drilling of the wheel centers being so designed that the rear lugs of one bucket come directly in line with the forward lug of the next

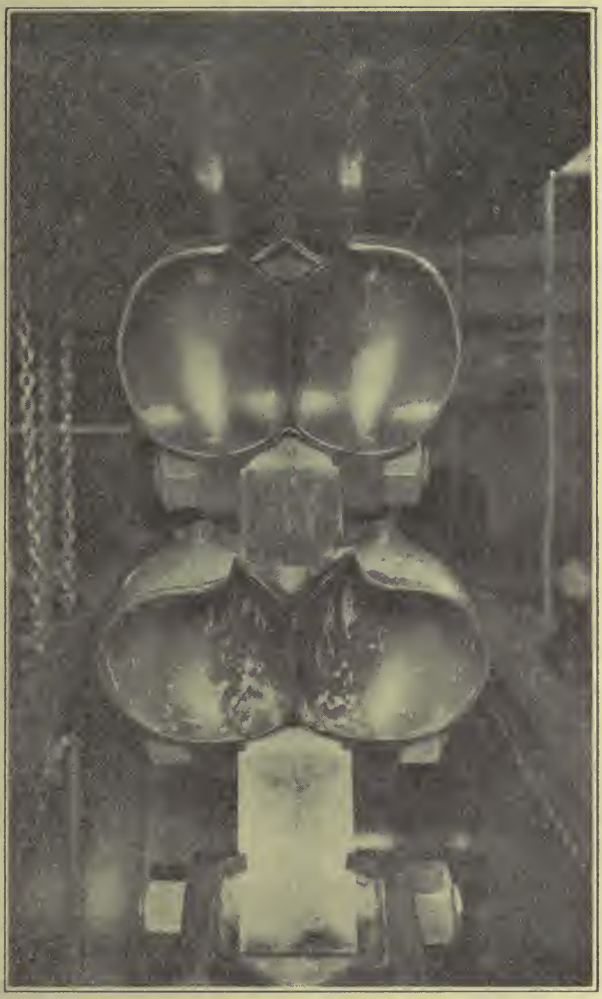


Fig. 2. Photograph Showing Condition of the Buckets on No. 1 Water Wheel at the De Sabla Power Plant of the Pacific Gas and Electric Company.

This wheel operates under 1531 ft. (467 m.) effective head at 240 r.p.m. developing 3750 hp. It was first put into operation on Oct. 22, 1903, and has been in almost continuous service since that time with practically no expense whatever for maintenance. This photograph was taken on Feb. 25, 1915, by the engineers of the Pacific Gas and Electric Company to record the condition of the buckets. The white spots in the bowls of the buckets are due to a mineral deposit left by the water in the buckets in drying. The entire surfaces of the buckets are smooth, the edges of the splitter and entrance edges as shown by the photograph, being sharp.

following bucket, these holes being drilled and reamed in line. A single bolt therefore passes through the rear lugs of one bucket, the double wheel rims of the center and the central or forward lug of the next following bucket, thus connecting up all of the buckets into a continuous chain. By this arrangement it will be observed that there are the same number of bolts as there are buckets, though each bucket is secured to the double wheel rims by two bolts.

In comparing this type with the double-lug type, it will be observed that the base line of the bucket, or the distance between the supporting bolts, is very much greater in the chain-type or

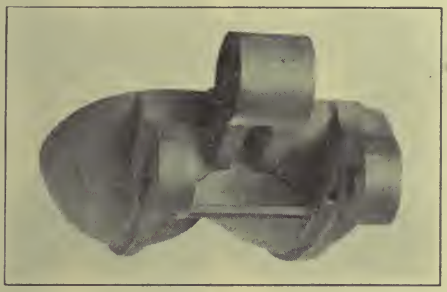


Fig. 3. Arrangement of Lugs on Chain Type or Double Lug Type of Construction.

triple-lug buckets than it is in the double-lug buckets. This type of construction is particularly suitable for all installations where the ratio between the diameter of the jet and the pitch diameter of the wheel is small, that is, where a large diameter of jet is applied to a comparatively small diameter of wheel. This is always the case where a very large power output is required, with a turning speed comparatively high, as proportional to the head of water, thus calling for large buckets on a comparatively small wheel. It is also especially suitable for extreme cases of large horsepower and high heads, making the wheel runner of the most stable construction.

In the construction of the wheel runners for comparatively low heads, cast-iron wheel centers of either the disc or "U"-rim type give good results. For medium high heads, wheel centers of either the disc or "U"-rim type made of annealed cast steel are thoroughly satisfactory. For extreme heads and large horsepower output, the wheel centers should be made from chrome-

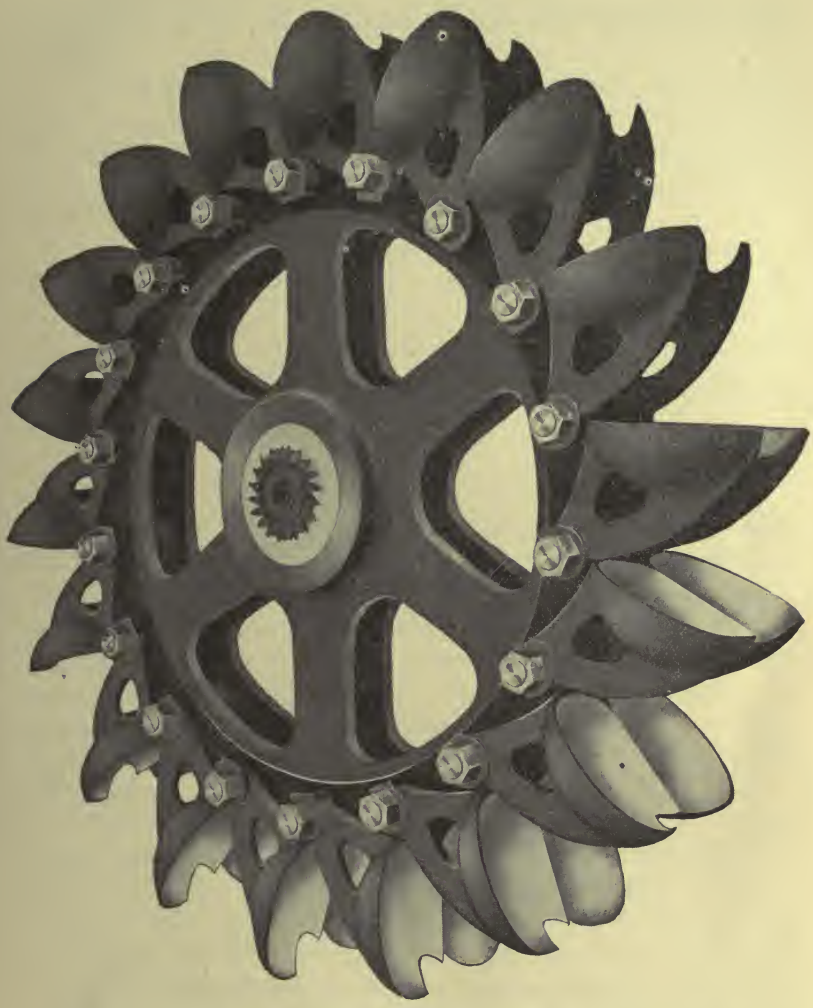


Fig. 4. Wheel of Chain Type of Construction. Wheel center constructed of two separate centers with hubs. Similar to wheels used in the Drum Power Plant of the Pacific Gas and Electric Company, developing 20,000 hp. under 1330 ft. (405 m.) effective head at 360 r.p.m.

nickel steel forgings. In such cases, the attaching bolts are also made of heat-treated chrome-nickel steel and forced into place with 25 tons pressure. The most satisfactory material to use for the buckets is a very high grade high-carbon steel casting. For

the highest heads, it is possible to use drop forgings for the buckets.

In the construction of the wheels, the accurate dynamic balance of the structure is of the utmost importance, and to insure this, the buckets are balanced in a special apparatus which insures a dynamic balance at the maximum runaway speed of the prime mover.

In the earlier wheels constructed, the breaking off of the buckets was one of the principal sources of failure; also the greatest single improvement in efficiency of the wheels was secured by the development of the ellipsoidal type of bucket bowls illustrated in the several photographs, this change alone having improved the efficiency of the wheels by over 10%.

NOZZLES AND SYSTEMS OF CONTROL.

In general, the needle type of nozzle is invariably used, the characteristic jet from a needle nozzle being illustrated in Fig. 5. This is a flash-light photograph taken through an opening in the side of the wheel housing. The blur at the right hand side of the wheel represents the rapidly revolving buckets of the wheel; the cone in the center of the jet is the end of the needle bulb. A characteristic needle and nozzle tip is illustrated in Fig. 6, this being the needle and nozzle tip for the nozzle shown in Fig. 7.

The determining factor in selecting the type of needle nozzle, which also carries with it the means of regulation of the power output and speed of the prime-mover that will be used in a given plant, depends primarily upon whether or not water economizing control can be used. In those plants that are located on streams where water storage cannot reasonably be secured, or where other power plants are located on the same stream, making it necessary to allow the full flow of the stream to pass the plant, or on those streams where irrigators' or riparian rights have a prime control, thus preventing the storage of water, the simpler stationary needle-controlled nozzle with governor deflector control over the jet, or the needle-regulating deflecting nozzle is used. The stationary needle-regulated jet-deflecting nozzle is shown in Fig. 7 (a jet deflector for a

Fig. 5. Characteristic Jet from Needle-Regulating Nozzle. Photograph taken by flash-light through opening in the side of the wheel housing. The blur at the right hand side of the photograph showing the revolving wheel, the cone of the needle being shown clearly in the center of the stream. The sharp, true cylindrical characteristic of the jet, its transparency and absence of spraying is clearly shown by the photograph.

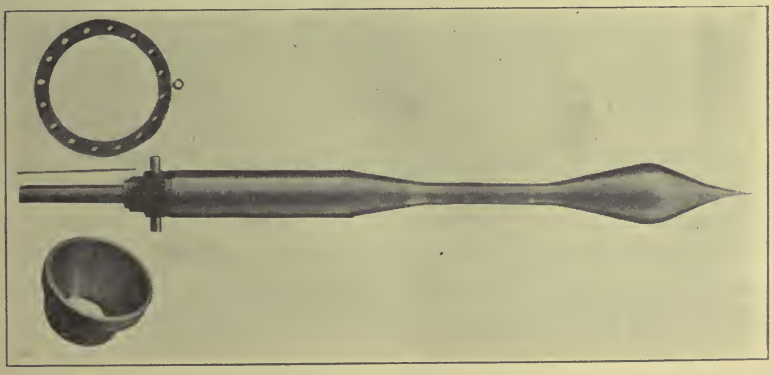


Fig. 6. Characteristic Needle and Nozzle Tip. Needle and nozzle tips from the nozzles shown in Fig. 7. Jet 10½ inches in diameter.

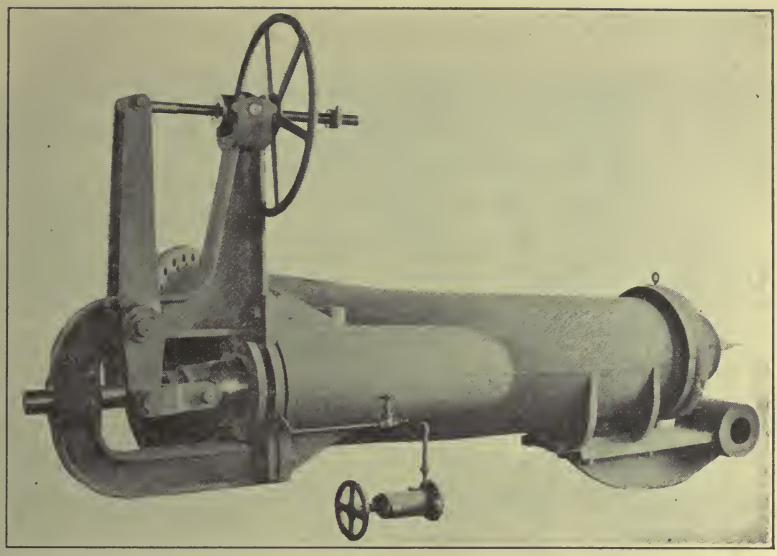


Fig. 7. Stationary Hand-controlled Needle-regulating Nozzle. Arranged for governor control through the means of a jet deflector, this nozzle projecting a jet 10½ inches in diameter.

nozzle is shown in Fig. 8). The nozzle is of particular interest, as it projects a jet 10½ inches in diameter, which is the largest single jet of water used at the present time.

Figure 8 illustrates two nozzles of this type arranged to be supplied with water through a branch "Y" from a single pipe line, the photograph clearly showing the arrangement of the deflector, the hand-operated needle control, and the needle-controlled, reversing water-motor-operated gate valves, one of which is bolted to each of the two discharge flanges of the branch "Y".

The method of mounting the jet deflector is clearly shown. The jet discharging from the end of the nozzle passes through the cylindrical bushing, which is slightly larger than the jet. The speed control is secured by the governor operating on the rockshaft and swinging the deflector more or less, so that it partially or entirely deflects the jet outside of the path of the buckets of the wheel.

The needle-deflecting regulating nozzle is illustrated in Fig. 9. This type of nozzle consists of a nozzle body which

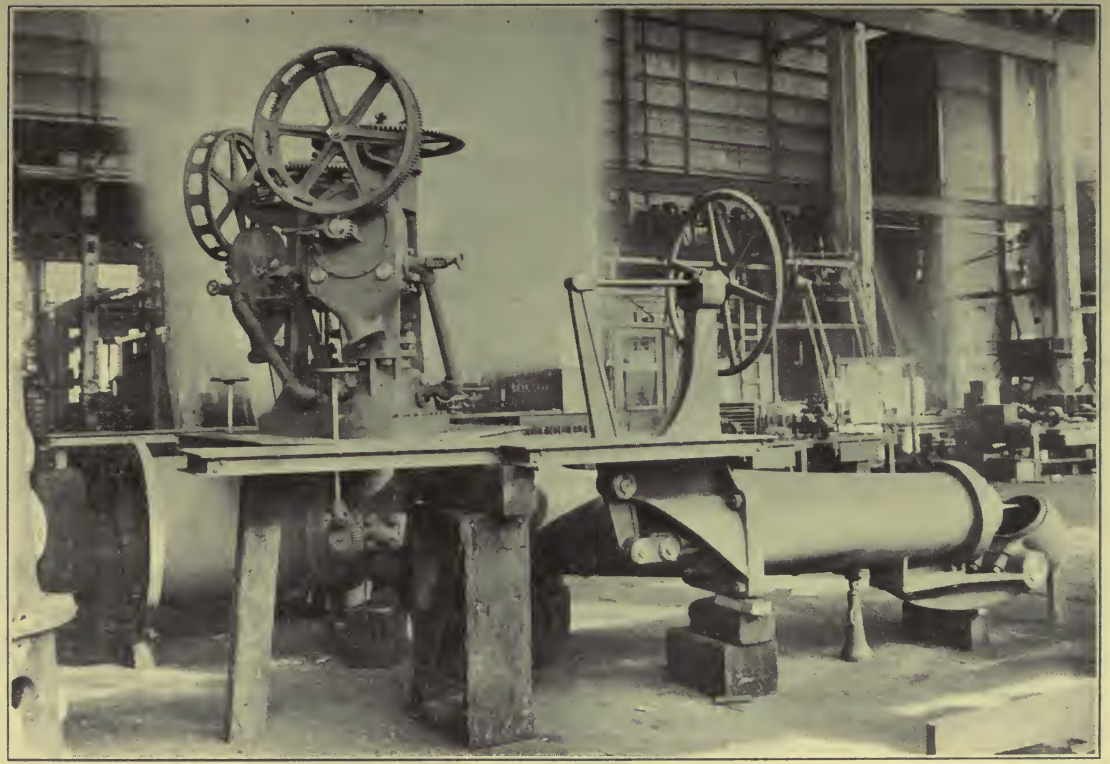


Fig. 8. Arrangement of Two Units to be Driven from a Single Pipe-line with Nozzles of a Stationary Needle-regulating Type. Hand control of the needle, governor control of the jet deflector. Gate valves of the Reversible Water Motor Type. Each wheel developing 2500 hp. under 390 ft. (118 m.) effective head, at 257 r.p.m.

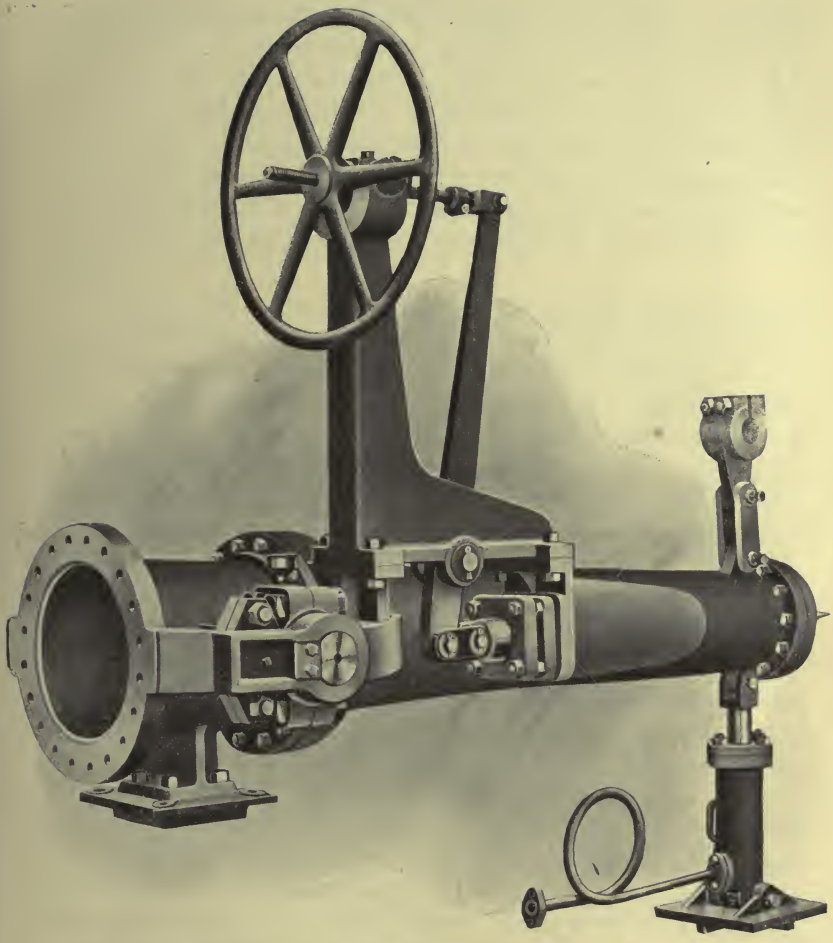


Fig. 9. Needle-regulating Deflecting Nozzle. The needle regulation is by hand control, the deflecting of the nozzle being by automatic governor control with hydraulic counterbalance to balance the weight of the nozzle and the contained water.

is pivoted to a ball joint, permitting the nozzle to be raised or deflected so as to either direct the full jet into the buckets of the wheel or to partially or entirely direct the jet outside of the path of the buckets of the wheel.

In both the stationary needle nozzle with the jet deflector and the needle-regulating deflecting nozzle, the needle is usually operated by hand control, the needle being set to utilize

to full advantage the available supply of water. In plants where either of these types of nozzles is installed and where there are forebay reservoirs, economy in the use of water is secured by setting the needle at different times during the day to carry the maximum load on the plant, the needle being set to follow the general load curve of the plant, while the momentary load changes and speed control are taken care of by the governor either operating the jet deflector or deflecting the nozzle.

The system of hand setting of the needle with governor control of the deflecting means is of particular value in semi-arid countries where, due to the influence of evaporation, the daily flow is variable to a very considerable degree; and also in those power plants where the source of water supply is in the snow fields, the quantity of water varying to a very great degree, depending upon the melting of the snow by the sun. In such plants the operator can set the needle by hand at different times during the day, to utilize to the best advantage the quantity of water available.

In such plants, where large units are installed, the control of the needle setting is by means of an electric motor with remote control from the switchboard, so that the power plant operator can, from the switchboard, set the position of the needle so as to carry any predetermined load that is desired, the needle setting being changed from time to time as the general condition of the load changes. In such plants the overall consumption of water approximates, in a series of steps, the load curve on the prime-mover. With the needle-regulating deflecting nozzle, the weight of the nozzle with its water contents is counterbalanced by an hydraulic cylinder, to relieve the governor of this additional weight, though the inertia due to the weight of the nozzle and its contained water must be overcome by the governor. Both the stationary type of nozzle with jet deflector and the deflecting nozzle give excellent regulation, for the reason that there is no change in the velocity of flow of the water in the pressure pipe line, due to governor action. Therefore, very sensitive speed regulation can be maintained, as the problem of inertia and the time of acceleration

of the column of water in the penstock is not here a factor in the problem of speed control.

To secure a better economy of water with the use of these types of needle nozzles, automatic devices have been developed so that the governor in rejecting the load on a plant first operates the deflecting means and then brings about a following and gradual re-setting of the needle and nozzle opening. However, these complicated arrangements, at best, are merely adaptations and approximations.

The ideal type of nozzle, and one that has been used in the most important high-head power plants where sensitive speed regulation and the highest economy in water consumption is required, is secured by the needle-regulating nozzle with auxiliary relief-nozzle control, as illustrated in Figs. 10 and 11. In general, this type of nozzle consists of a stationary main nozzle body, the power jet directed against the water wheel being controlled by the needle of the main nozzle. This needle is direct operated by the speed governor, bringing about a re-setting of the needle for each change in power demand on the prime-mover, so that there will be delivered to the buckets of the wheel at all times just sufficient water to carry the load on the prime-mover, thus securing a water consumption by the prime-mover strictly proportional to the power output required from it. By this arrangement, maximum economy in the use of water is secured, taking advantage of every sag in the load curve to conserve the water not required to drive the wheel, in order to have this water available to carry the peak loads.

In the operation of this type of nozzle, to insure against water ram or surges in the pressure pipe line arising out of a sudden reduction of load on the prime-mover, automatically bringing about a correspondingly rapid contraction of the nozzle orifice and retardation in the flow of water in the pipe line, an auxiliary relief nozzle is provided, which is directly connected to and takes its water out of the body of the main nozzle. This auxiliary relief nozzle is likewise provided with a needle control, the jet from this auxiliary nozzle being directed into the tail-race, and at no time brought into contact with the wheel.

The movement of the needle of the auxiliary relief nozzle

is inverse to that of the needle of the power nozzle. This is clearly illustrated in Fig. 10. This inverse action is accomplished by means of the controlling lever, one end of which is connected to the operating means of the governor, the movement of the power needle being secured through link connections between the cross-head on the shank of the power needle and the controlling levers. The lower end of this lever is

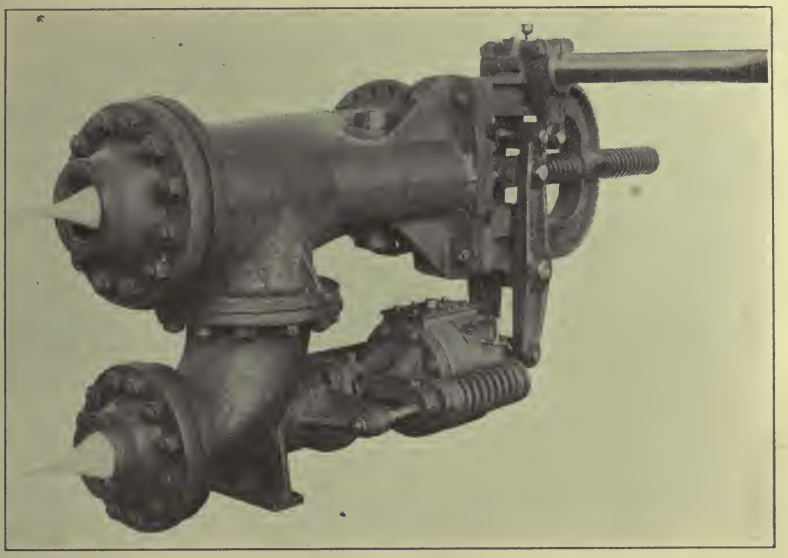


Fig. 10. Typical Arrangement of the Needle-regulating Nozzle with Auxiliary Relief Control. Shows the arrangement of the lever control for the main needle, and control of the relief needle, through the differential-cataract.

attached to a cross-head on the piston rod of the differential-cataract, which is attached to a cross-head on the stem of the needle of the auxiliary relief nozzle. These levers are fulcrummed between the two needle connections. It is evident, therefore, assuming that the differential-cataract be locked in one position, that a closing movement of the needle of the power nozzle would bring about a corresponding opening of the auxiliary relief nozzle, and vice versa. However, such an inverse action is neither required nor desirable, as it would not secure the desired economy in the consumption of water. Therefore, the differential-cataract is introduced between the cross-

head on the stem of the needle of the auxiliary relief nozzle and the lower end of the operating levers.

This differential-cataract is so adjusted that provided a load change is either so gradual or of such an amount as not

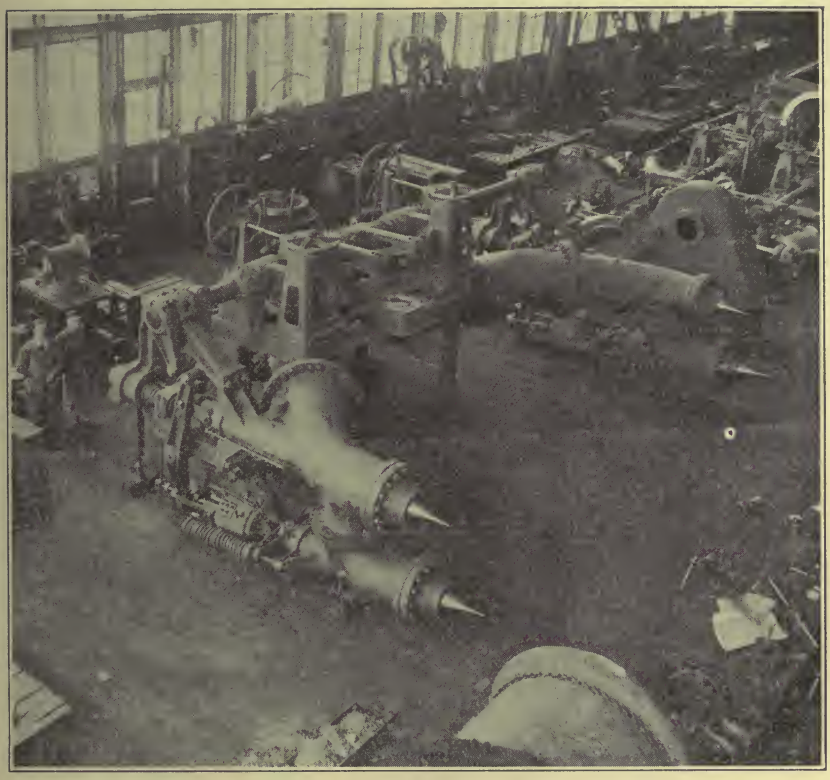


Fig. 11. The Nozzle of the 16,000 hp. Units being Installed in the Power Plant of the Los Angeles Aqueduct. Shows arrangement of auxiliary-needle relief control. Movement of the power needle and the auxiliary-relief needle is controlled from a central governor through a large rockshaft connecting up the governor with both nozzles. Hand control mechanism is provided and arranged so that either or both nozzles can be controlled by governor or by hand. This nozzle projects a jet 8¼ inches in diameter under 870 ft. (265 m.) effective head, developing 16,000 hp. at 200 r.p.m.

to set up disturbances and excessive pressure rises in the pressure pipe line, a yielding or slipping action takes place in the differential-cataract, which permits the auxiliary relief nozzle to remain closed. Under such conditions, therefore, there is no

discharge of water from the auxiliary relief nozzle. In case, however, a load change takes place which brings about a closing movement of the power nozzle of sufficient magnitude to cause excessive pressure rises in the pressure pipe line, or where the load change is very sudden, which would bring about the same results, the time element control of the differential cataract causes the auxiliary relief nozzle to be opened to an amount sufficient to prevent such pressure rises. Immediately the closing action of the needle of the power nozzle has ceased, then the needle of the auxiliary relief nozzle commences to close at a rate which has been adjusted and which will not bring about objectionable pressure rises in the pipe line.

The performance of the needle nozzle with auxiliary relief control is absolute, the movement of the needles of the two nozzles being from the same prime-mover, namely, the servomotor of the governor. This gives an absolute assurance against accidents, and insures the maximum water economy in the operation of the prime-mover with a variable load. The movement of the needles in the two nozzles thus interconnected and operated from the same source of power, insures absolute safety, higher water economy and is more reliable than a governor-operated means of deflecting the jet, and an indirect control over the operation of the needle.

The speed regulation secured by the needle-regulating nozzle with auxiliary relief control is satisfactory for the most exacting conditions. With a proper proportioning of the operating elements, an absolute control is secured over the pressure rises that can take place in the pipe line due to an instantaneous rejection of full load on the prime-mover, which would bring about an instantaneous closing of the needle of the power nozzle. The pressure rises can be kept at any percentage desired, and in special cases a negative pressure rise can be accurately secured with instantaneous closing from full opening of the needle of the power nozzle.

Fig. 11 shows the nozzles for a double-overhung type of unit, developing 16,000 horsepower. These nozzles are arranged with a central governor control, operating the nozzles of the power and auxiliary relief nozzles through the rockshaft extending between the two nozzles. Arrangements are

made for independent hand-control of the needles of each nozzle, should it be desired to operate either one or both sides by hand control. The nozzles illustrated in Figure 11 project a jet 8¼ inches in diameter, the head of water at the plant being 940 feet.

The auxiliary relief nozzles are designed to secure a negative pressure rise of over 10% with an instantaneous rejection of full load on the prime-mover. The negative pressure rise with sudden rejections of large proportions of the load improves the speed regulation of the prime-mover.

The latest developments in large prime-movers equipped with the needle-regulating nozzles with auxiliary relief control is to mount the servo-motor of the governor directly on the power nozzle, the piston of the servo-motor being mounted on the stem of the needle of the power nozzle. The controlling elements and pendulum head of the governor are mounted directly on the nozzle. This construction is illustrated in Figure 12. A comparison of the design in Fig. 12 and the nozzle arrangement as shown in Fig. 11 will demonstrate the advantage of this latest development.

By the arrangement of the piston of the servo-motor of the governor directly on the stem of the needle of the power nozzle, the most sensitive regulation can be secured, as all lost motion and delay due to torsion in the rockshafts and lost motion in the connecting elements is eliminated. In units of large power, this is a most important factor.

GOVERNORS.

The modern governor is essentially a pressure oil-operated device, arranged with a speed sensitive element, a servo-motor for operating the regulating elements, pilot and relay valves to insure a quick response of the servo-motor to the tendency of speed changes as indicated by the speed sensitive element. Modern governors will indicate and correct speed changes of from ¼ to ½ of 1%, and are sensitive to a degree permitting a full stroke of the governor to be made in approximately from 1½ seconds to 2 seconds time.

Governors are of two general types: One where the gov-

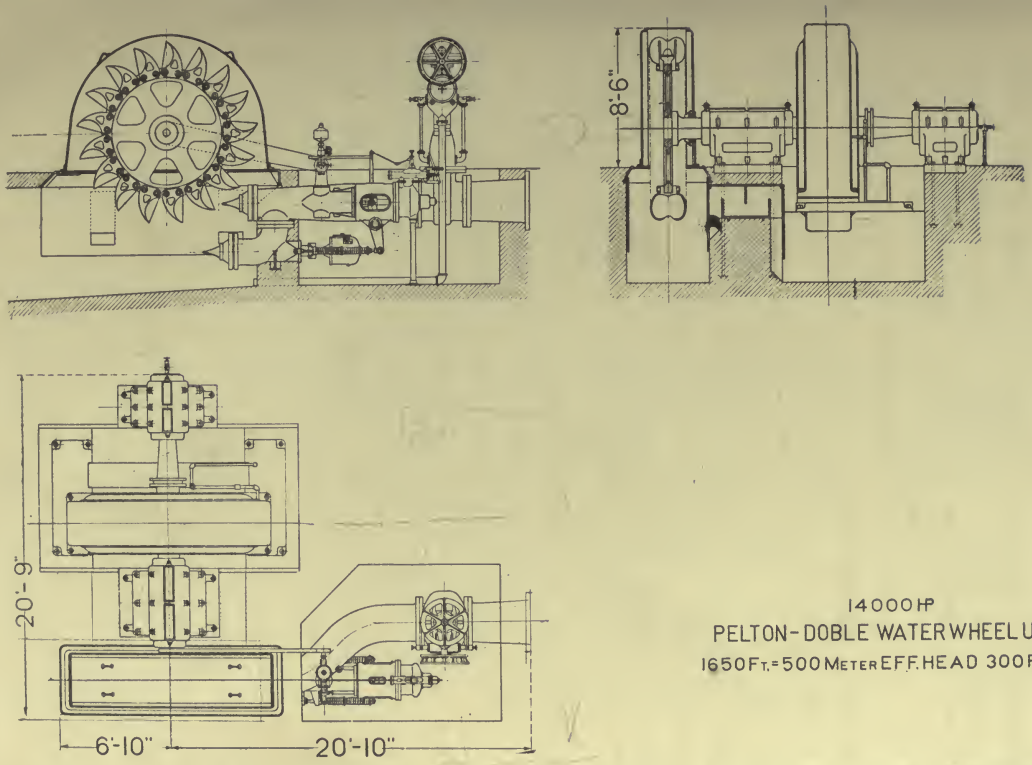


Fig. 12. A 14,000 hp. Horizontal Type Single-overhung Unit with Auxiliary-relief Control. Servo-motor of governor mounted directly on the nozzle body and directly controlling the needle of the power nozzle and of the auxiliary relief nozzles. Also illustrates tail-race ventilators. This unit operates under 1650 ft. (500 m.) effective head at 300 r.p.m., developing 14,000 hp.

ernor itself is a completed machine, as a product of separate manufacture, and arranged with a terminal shaft by which the gate or nozzle-operating gearing of the prime-mover is controlled and operated. Governors of this type are practically a stock manufacture, and are sufficiently flexible in design so that they can be satisfactorily connected up to medium and small size units; such a governor is illustrated by Fig. 13. The oil supply for this governor is contained in the base. The oil pressure to operate the servo-motor is secured through means of the gear pump shown. The speed sensitive element operates the pilot valve, which in turn operates the relay valve which controls the oil supply to the cylinder of the servo-motor. The servo-motor is connected to a terminal shaft, to which the operating elements of the prime-mover are connected. The character of regulation secured from governors of this type is thoroughly satisfactory for the exacting demands of hydro-electric power generating stations.

A modification of this type of governor arranged with a vertical terminal shaft is illustrated in Fig. 14. This type of governor is used with vertical shaft Pelton wheels, the terminal shaft of the governor being vertical and extended to the wheel pit, where it operates the controlling elements of the unit. It will be noted that this governor is fully enclosed, the speed element being mounted at the top. The hand wheel at the side is for hand-control, should it be desired at any time to operate the prime-mover in this manner.

Governors for very large units are illustrated in Fig. 15, which shows what is termed a "direct-motion governor", complete with its independent oil pump, oil-air-pressure storage tank, and controlling mechanism. This governor has a capacity of 40,000 ft.-pounds, the speed element and controlling valves being sensitive to a degree necessary to indicate speed changes of ¼ of 1%. Through the means of the duplex pilot valve and relay valve construction, the governor can be adjusted to make a full stroke in less than 1½ seconds. On actual test, the governor illustrated made a complete stroke in 1.2 seconds time. However, such rapid moving governors are not required except in extraordinary cases. The principal feature of the design of this

Fig. 13. Standard Type of Oil-pressure Operated Self-contained Governor.

Fig. 14. Special Type of Governor Arranged with Vertical Terminal Shaft to be Used in Conjunction with Vertical-shaft "Pelton" Units.

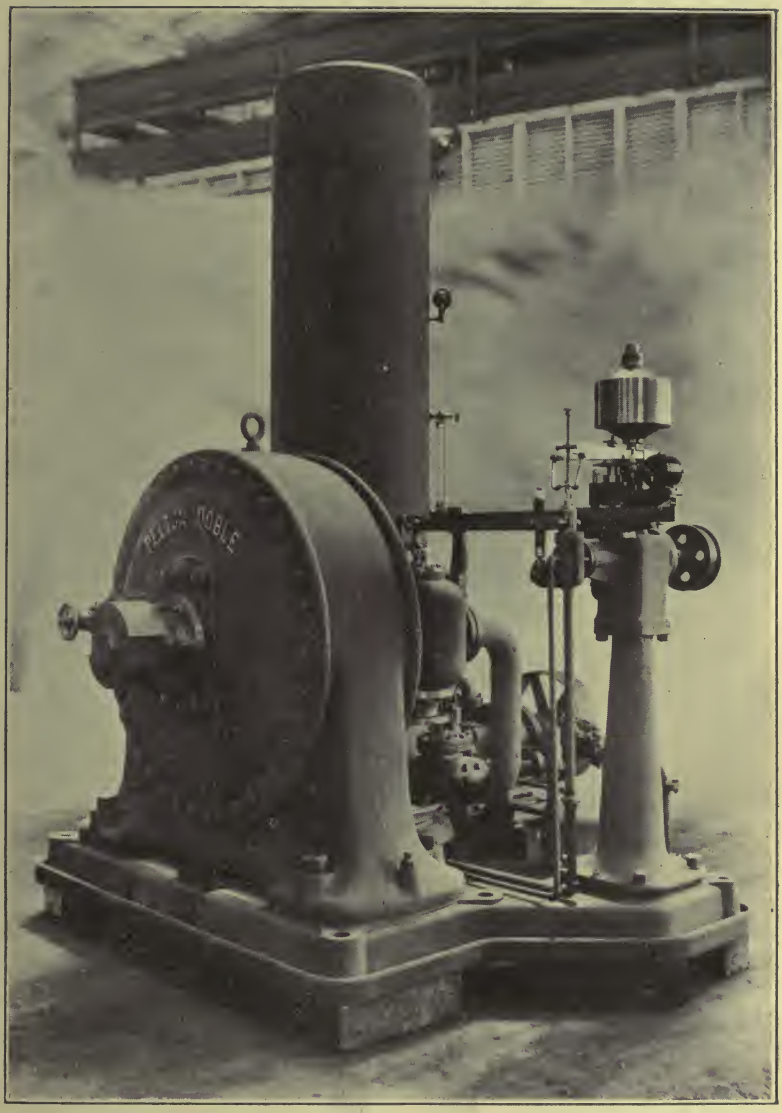


Fig. 15. A New Type Direct-motion Oil-pressure Operated Governor of 40,000 ft.-lb. Capacity, Complete with Independent Oil Pump and Oil-Storage Tank.

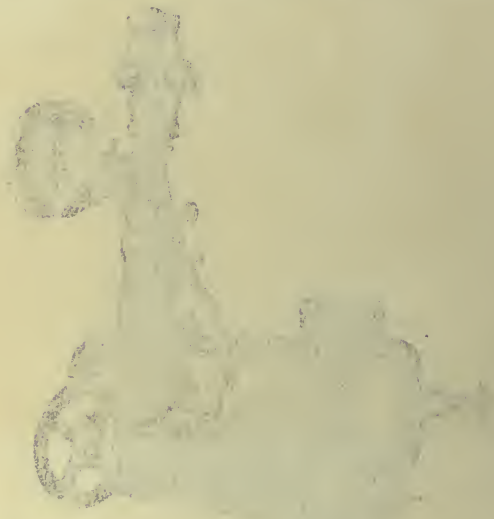
governor is that the terminal shaft is connected directly to the oscillating shaft operating the gate controlling elements, thus avoiding lost motion due to linkage connections. To secure the rapid action of this governor, large oil ports are required, necessitating a very large relay valve. This is taken care of by the duplex pilot valve and relay valve construction.

The most recent work, however, in governing apparatus is the direct application of the piston of the servo-motor of the governor to the end of the stem of the power needle. A small governor of this type is illustrated in Fig. 16, this governor being

Fig. 16. Small size direct motion governor mounted directly on the nozzle body and arranged for water operation.

designed to operate with water pressure, and for this reason a strainer is provided. The same type of governor is also arranged to operate from an independent oil pressure source. Governors of this kind give excellent regulation.

A modification of this type of governor is illustrated in Fig. 17, which shows a 24-inch Pelton wheel arranged for belt drive; speed and power control of this unit are through the means of the governor operating a jet deflector, the needle nozzle being controlled by hand. A modification of this type of unit is illus-



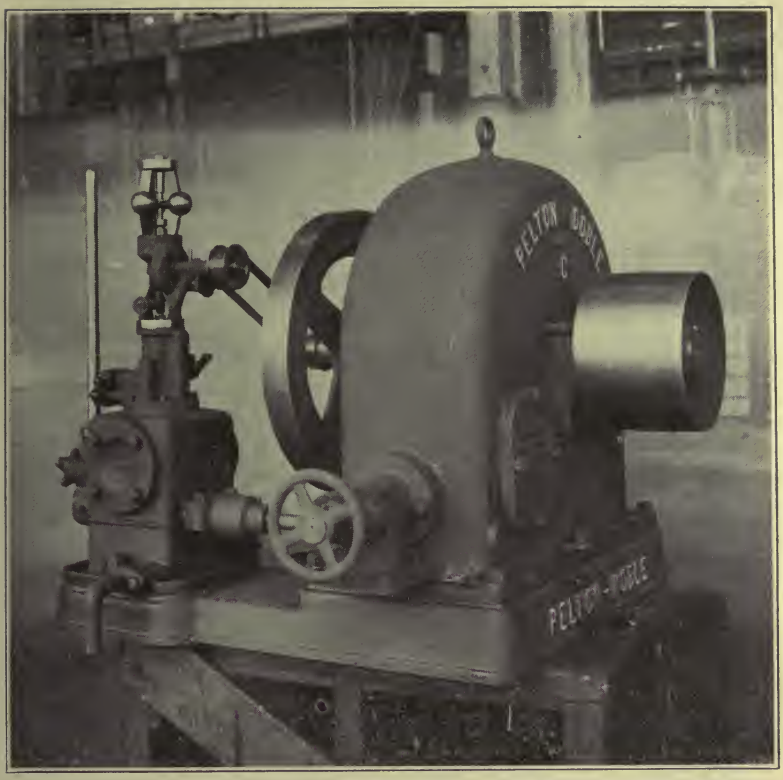


Fig. 17. A Standard "Pelton" 24-inch Water Motor arranged with Oil-operated Direct-motion Governor. Speed and power output of wheel controlled through means of jet deflector. Motor equipped with needle-regulating nozzle hand control.

trated in Fig. 19, which shows a similar wheel direct connected to a 15-kw. generator mounted on a continuous bed-plate. For units of this small size, owing to the insignificant fly-wheel value of the revolving elements, good regulation requires the mounting of a fly-wheel on the shaft.

Excellent regulation is secured from these small units, as will be noted from Fig. 18, showing a tachograph record of a test made on the unit illustrated by Fig. 19. The four upper charts represent the speed control of the governor when instantly applying and rejecting full load on the unit, then three-quarter load on the unit, and then one-half load on the unit. In con-

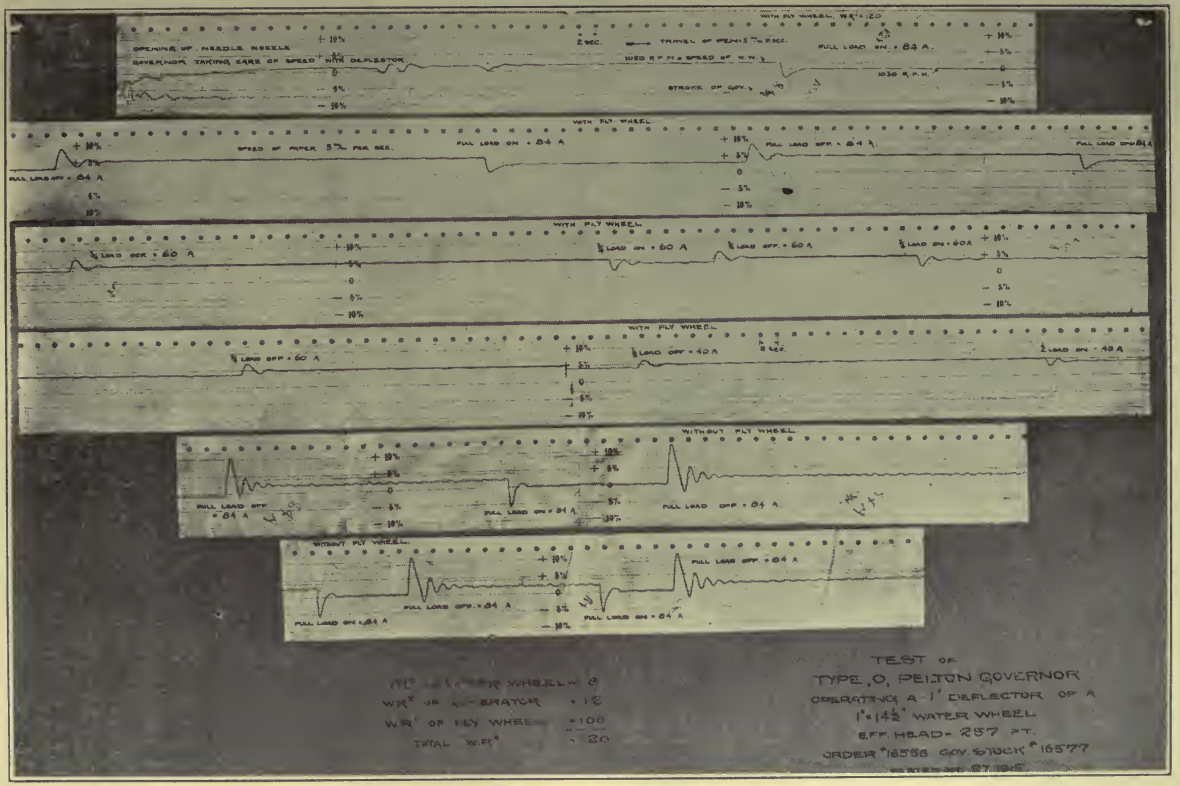


Fig. 18. Tachograph Records on Speed Regulation Test Conducted on Unit Illustrated in Fig. 19.

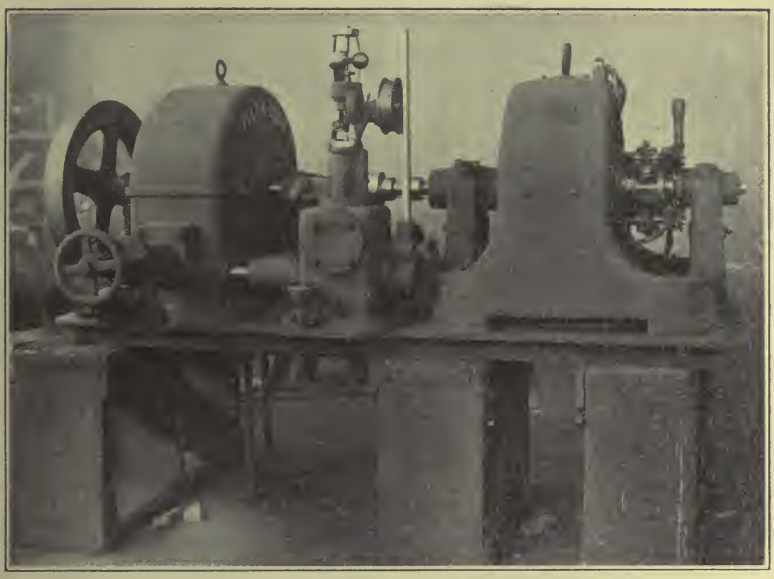


Fig. 19. "Pelton" Hydro-Electric Unit, 15 KW. Capacity. Arranged with direct-motion pressure oil-operated governor operating on jet deflector with needle-regulating nozzle hand controlled. This type of unit is particularly well suited for small isolated plants. This unit operates under 257 ft. (78 m.) effective head, developing 20 hp. at 1020 r.p.m.

ducting this test the load was secured by a water rheostat, the load application and rejection being secured by opening and closing the main switch, thus bringing about an instantaneous change of load condition.

A further test on this unit for governing was carried out by removing the fly-wheel, and the two lower charts show the effect of this change.

MAIN SHAFTS.

In prime-movers of small and medium size, shafts forged from 0.30 to 0.40 carbon open-hearth steel, properly annealed, are thoroughly satisfactory for the purpose. For large prime-movers, however, the shafts should be made from fluid-compressed, chrome-nickel steel ingots, hollow forged and oil tempered. Shafts of this type have now been in continuous service for twelve years. They have proved to be absolutely satisfactory and the bearing journals have taken on a high polish. With the

single-overhung type units, it is preferable to provide the shaft with a flange forged solid with the shaft, the wheel center being bolted to this flange. This makes a thoroughly reliable construction and facilitates erection at the site of the power house. With the double-overhung type, at least the wheel runner on one end must be pressed on to the shaft, so as to allow the shaft to be pressed into the hub of the rotor of the generator; otherwise a very expensive shaft design must be provided, with an enlargement in the center at least as large as the flanges. This construction is not usually justified.

MAIN BEARINGS.

The very heavy weight of the revolving parts of modern large hydro-electric prime-movers together with the high surface speed of the shaft in its bearings have brought about a development of a very massive high-speed bearing. Bearings of this type are illustrated in Figs. 20 and 21. The main bearing shown in Fig. 21 is constructed for a shaft diameter of 20 inches, with

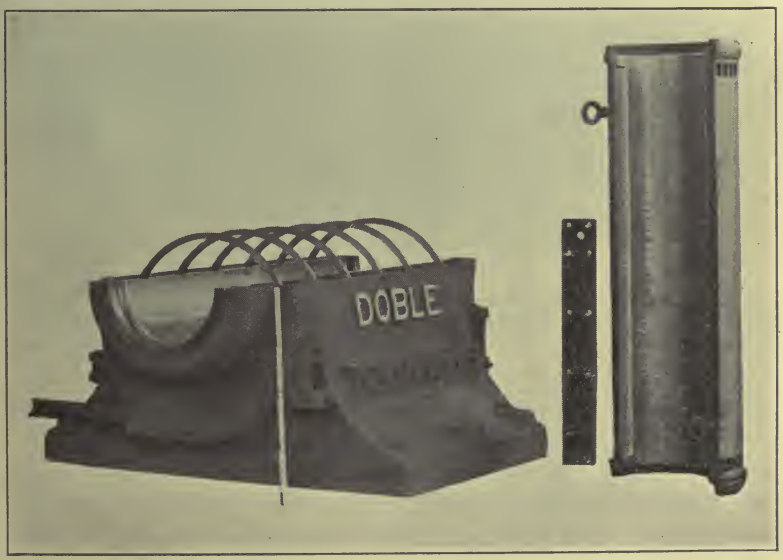


Fig. 20. Heavy-pressure High-speed Bearings. Shows arrangement of lubricating-oil rings, and the construction of the removable revolving shell. Also shows arrangement of water-cooling tubes through oil storage in base of bearing.

a length of bearing shell of 69 inches, the total weight of this bearing as shown being 11,000 pounds. This is one of the bearings of a 16,000 horsepower unit rotating at 200 revolutions per minute.

The bearing surfaces are provided with oil by revolving oil rings, the temperature of oil in the bearing base being controlled by water-cooling tubes. In addition, provisions are made for

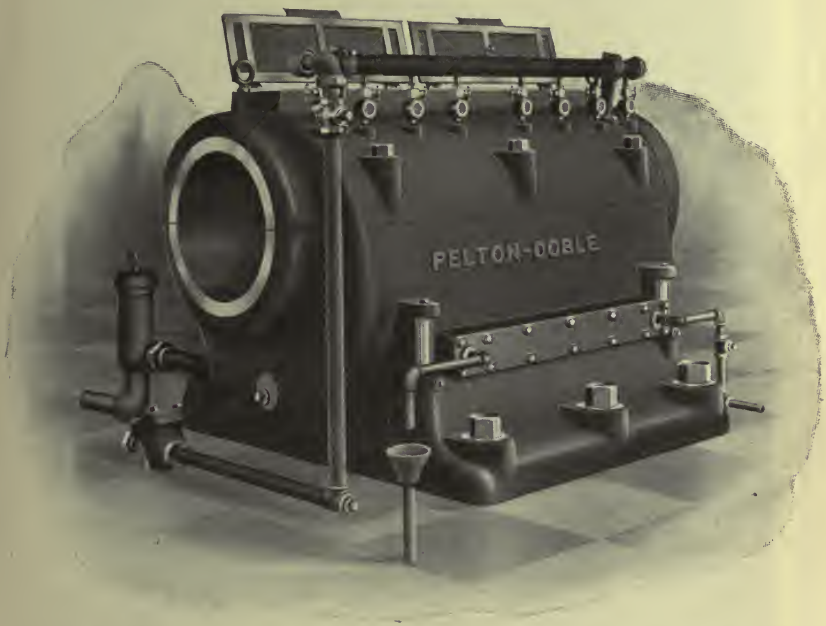
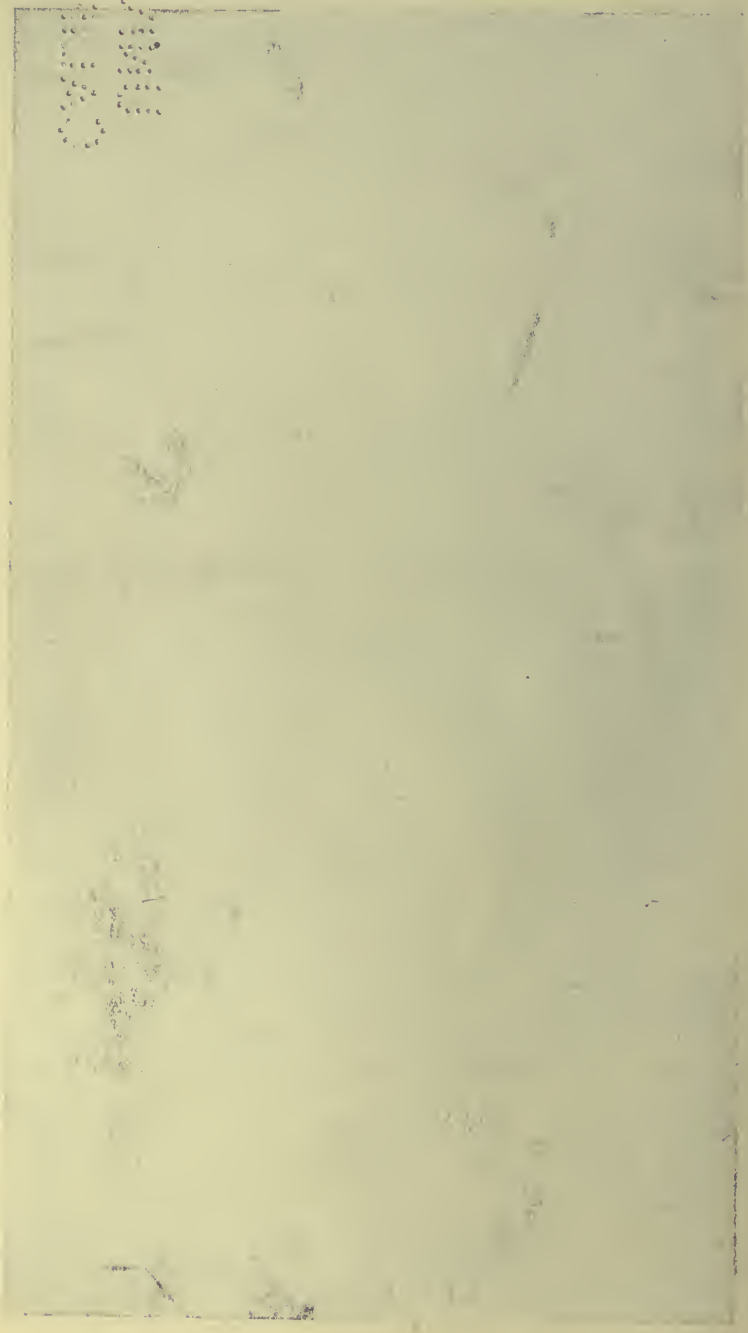


Fig. 21. Typical High-speed Heavy-pressure Bearings. This bearing was constructed for a shaft diameter of 20 inches, with a length of bearing shell of 69 inches. Weight of bearing 11,000 pounds.

supplying fresh oil to the bearing through sight-feed lubricators and drawing out the used oil through an overflow, so that from time to time, while the plant is in operation, the oil in the bearing can be withdrawn and replaced with fresh oil that has been filtered. These bearings are arranged so that the bearing shells can be rotated around the shaft and removed without lifting the shaft from the bearings. They are also provided with air seals at the end of the bearing to prevent leakage of oil from the bear-

Fig. 22. Typical Construction of Water Wheel Housings for Large Units. These housings are being installed in the power plant of the Los Angeles Aqueduct. Wheels develop 16,000 hp. under 940 ft. (285 m.) effective head at 200 r.p.m.



ings. Hinged covers are provided with ample sized openings, so that the operator can place his hand directly inside the bearings and on the shaft, to check the temperature and condition of the bearing surfaces. Thermometers are also installed in the bearings to indicate the temperature of the film of oil between the surface of the shaft and the surface of the bearing.

A further control of the temperature of the bearing is also secured in large units by discharging a small spray of water through the hollow shaft. This method keeps the shaft cool, is thoroughly satisfactory and efficient, and should always be installed on the largest high-power units. The arrangement for applying the water to the end of the shaft is illustrated in Fig. 12, where, at the end of the shaft opposite to the water wheel, the spray nozzle is shown. Due to the partial vacuum existing in the wheel housing, this fine spray of water is drawn through the shaft, producing thereby a most efficient cooling medium.

These bearings have proved to be absolutely satisfactory under the most severe conditions of heavy pressure and high speed. The older form of so-called spherical self-aligning bearings are not now used on the heaviest type of units.

WHEEL HOUSINGS.

The general type and construction of housing, or casing, in which the wheel is to revolve is illustrated in Fig. 22. For best practice each wheel should rotate in a separate housing to prevent interference from discharged water. The lower part of these housings is preferably made of iron castings, the upper housing, or cover, being preferably made of steel plate riveted into a cast iron frame. The joints in this plate work are riveted hot, chipped and caulked, so as to be water-tight. This type of housing for large units is preferable to a housing made entirely of cast iron, as it is lighter to handle and eliminates any danger of breakage. Where the shaft of the water wheel passes through the side of the housing, leakage of water through the opening is prevented by means of a centrifugal disc and water guard. This device makes a frictionless packing. In small units it is preferable to make the housing of cast iron.

CONTROL GATES.

A very important feature in all hydro prime-movers is the main control gate or valve, the general type in use being of a single-disc gate construction. In the earlier plants hand-operated gates were deemed sufficient. A later development brought about the use of gates operated by an hydraulic cylinder, as shown in Fig. 35 of the Crane Valley No. 1 Power Plant. The latest development in disc gate valves is where the gate disc is operated by a reversible water wheel. A gate of this type is illustrated in Fig. 23. This type of gate has proved more reliable and satisfactory in service than the hydraulic-cylinder operated gate valve, as grit and foreign substances in the water which have a tendency to clog the valves and cylinders of hydraulic-cylinder operated gate valves do not affect the operation of the reversible water motor.

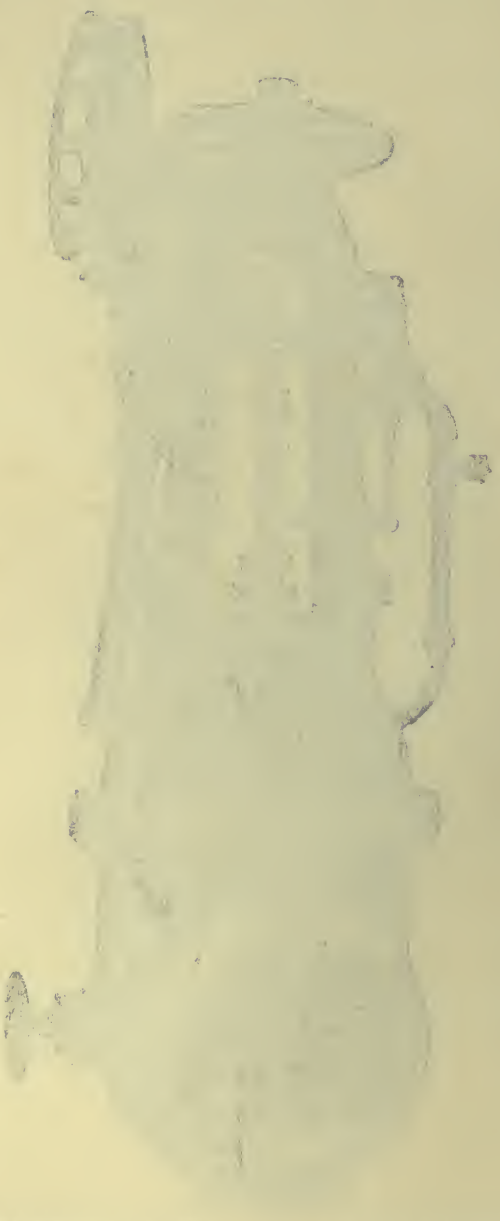
Furthermore, the reversible water motor has a very heavy starting torque, which is of value in commencing the opening stroke of a gate valve which may have remained shut for some period of time, as in such cases there is a tendency for a gate disc to stick to its seat.

In the reversible water-wheel operated gate valve, the main gate stem is provided with a safety limit stop, so that in the opening or closing movement of the gate it protects the gate against stress which would be set up in the structure, due to over-opening or over-closing the gate by careless operation.

For prime-movers operating under the highest heads and where the units are of very large power output, the disc gate valve is not the best form, owing to the enormous pressure brought upon the seats of the gate ring and to the cutting action on these seats due to eddy currents set up in the water passing through the throat of the gate.

The ideal type of control gate for use with the largest size units and under extremely high heads is the "uniform-flow needle gate valve" illustrated in Fig. 24. In the control of water under high heads, it has been demonstrated that the needle type of valve is the proper design to adopt. The construction, as shown in Fig. 24, consists primarily of a needle-regulating valve

Fig. 23. Single-disc Type Gate Valves, Operated by Reversible Water Motors.



controlled by an hydraulic cylinder, with a terminal slow-closing safety element. This slow-closing safety element consists of an extension of the piston rod which passes into a labyrinth in the cylinder head. The closing of the valve is permitted to take place by discharging the pressure fluid from this cylinder. As the valve approaches the closing position, the extension stem enters the labyrinth shown, and gradually restricts the escape of fluid from the cylinder. This resistance effect is cumulative, so that absolutely no shock or jar can be brought on the pipe line.

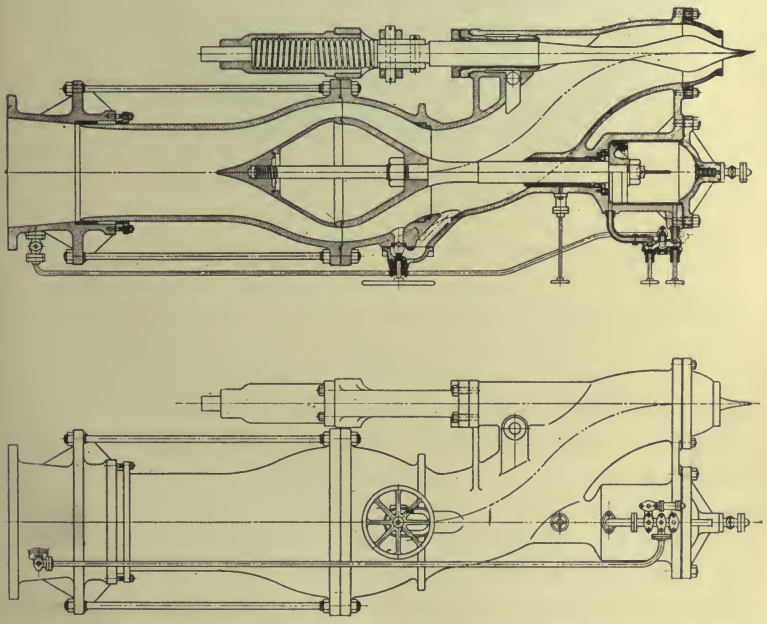


Fig. 24. Uniform-flow Needle Gate Valves Designed for the Largest Size Units Under Extreme Conditions of Head.

From the design it will be observed that owing to the uniform flow through the valve, no eddy currents can form. The seat is of such form that the water flows smoothly over, preventing the cutting out due to eddies forming in the disc type of gate valve. This type of gate valve can also be inspected. This is provided for by the telescopic section of the valve body which can be drawn back into the pipe line, permitting inspection with-

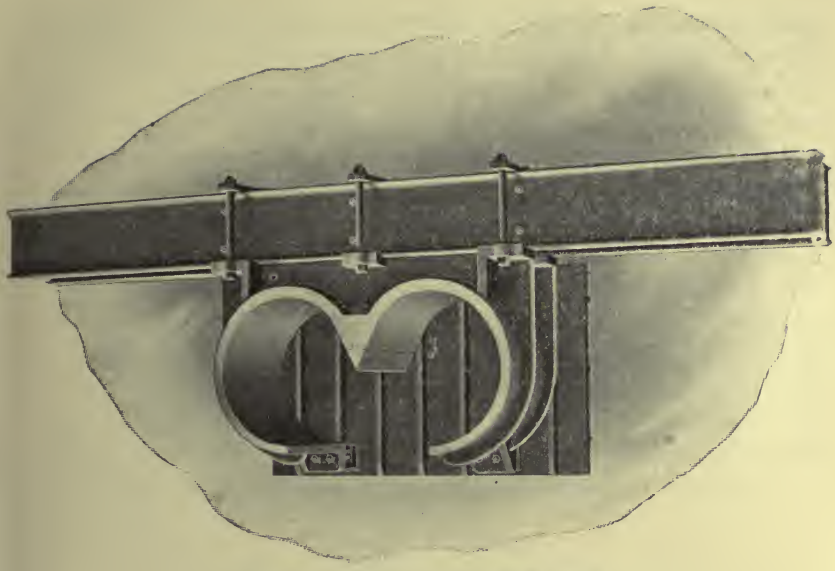


Fig. 25. "Ensign" Vortex Baffle Plate.

out disturbing any of the parts supported by the foundations. By this method a complete inspection and replacement of all of the working or wearing parts of the valve can be made.

It will be observed that a by-pass valve is arranged so that under normal operating conditions the main valve would be opened with an equilibrium of pressure on both sides of the valve. However, it is designed and constructed so that in case of emergency the valve can be safely opened with the full pressure of water on one side. This type of valve incorporates in its design and construction the elements that are essential for a safe and satisfactory operating valve under the most extreme conditions of high pressure and large power units.

BAFFLE PLATES.

With prime-movers operating under high heads, it is necessary to provide some device to bring to rest the water discharged from the deflecting nozzle when the jet is deflected from the wheel, also to take care of the discharge of the auxiliary relief nozzles where this discharge cannot take place through a free

channel. This problem is an extremely difficult one, but has been most satisfactorily solved by the "Ensign Vortex" type of baffle plate, illustrated in Fig. 25. The action of this baffle plate is similar to that of the Pelton bucket, excepting that the discharge instead of leaving the sides of the bucket, is brought through an angle of approximately 270 degrees, so that the water expends its energy in discharging against itself. These baffle plates have been tested out under heads of water of over 2000 ft. (600 m.) and are absolutely successful in destroying the velocity in the water without commotion, and show practically no signs of wear. The original baffles of this type were installed in the Mill Creek No. 3 Plant of the Southern California Edison Company, which was started March 17, 1903, operating with 1900-ft. (580 m.) head, the wheels developing 1600 horsepower. These baffles are in service today and show practically no indication of wear.

TYPES OF DESIGN.

In general, the most favorable design of hydraulic prime-mover, where the conditions of installation permit, is the single-overhung horizontal-shaft type, the general arrangement being

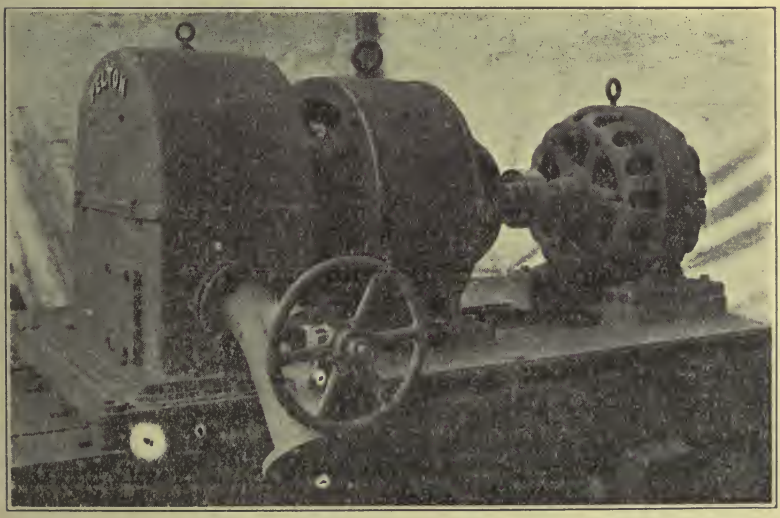


Fig. 26. Characteristic Type of Exciter Unit Used on Large Plants. Operates under 360 ft. (110 m.) effective head at 720 r.p.m., developing 44 hp.

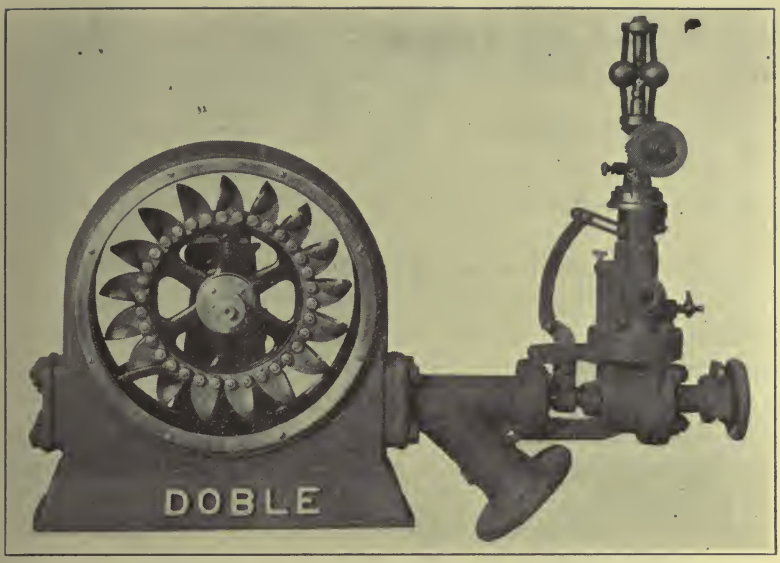


Fig. 27. Small-size Wheel with Direct-motion Governor Mounted on Nozzle Body and Controlling the Needle Direct.

effected by a modification of the detail elements, such as regulating elements, etc., and their mode of operation.

Figure 26 illustrates an exciter unit, consisting of a Pelton wheel driving a direct-current exciter and an induction motor, the power output of the wheel being regulated by a hand-controlled needle nozzle. In the operation of such a unit, sufficient water is discharged against the wheel to carry somewhat more that the excitation load on the generator. This causes the induction motor to act as a generator, discharging into the main bus bars to which the induction motor is connected. This induction motor acts as a speed control, in that it rotates practically in synchronism with the main generators, but has the advantage of some slip, so that speed variation on the main unit is modified due to the slippage of the inductor generator and to the fly-wheel value of the revolving elements of the exciter unit.

A further advantage of this type is that in case of interference, such as clogging of the water-wheel nozzle, which would otherwise bring the exciter to rest, immediately that the power

developed by the water wheel begins to fall off, the induction motor carries the exciter unit. This type of exciter is now being installed in the largest hydro-electric stations and has proven thoroughly satisfactory for the purpose.

A type of Pelton wheel arranged for exciter drive and provided with a direct-motion governor mounted directly on the nozzle is illustrated in Fig. 27. This type of unit is also used for small isolated plants.

An hydro-electric unit suitable for small plants is illustrated in Fig. 28. This shows an ideal two-bearing single-overhung unit, the revolving element of the generator being mounted between the bearings, the water wheel being mounted on one end of the shaft overhanging one bearing, and the fly-wheel being mounted on the opposite end of the shaft, overhanging the opposite bearing. This unit contains a direct-motion governor, ope-

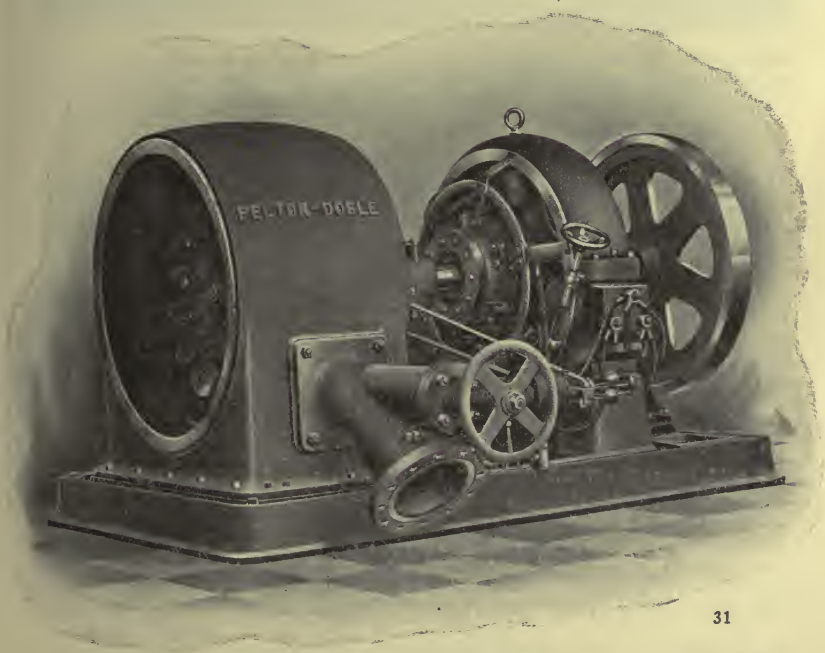


Fig. 28. Typical Single-overhung Horizontal-shaft Type Unit for Small Isolated Plants, Plantation Work, etc., Speed control is by means of a direct-motion governor operating directly on the controlling needle. Operates under 90 ft. (27.5 m.) effective head at 350 r.p.m., developing 18 hp.

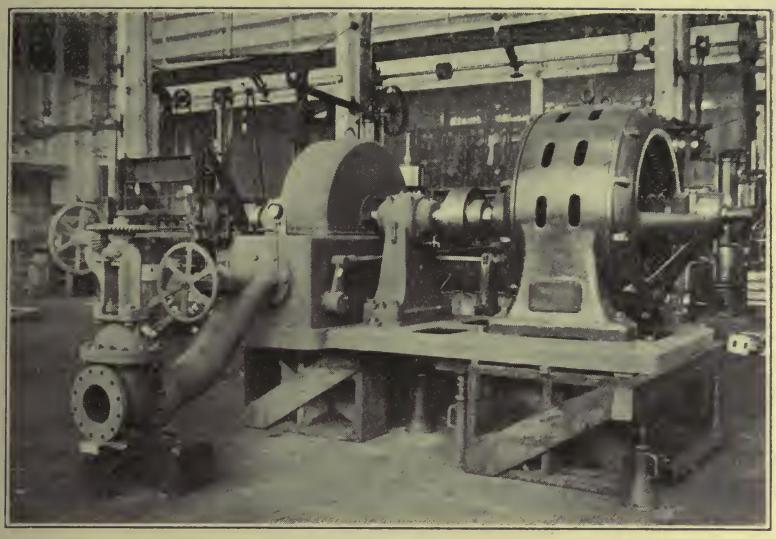


Fig. 29. Typical Hydro-electric Unit for Installation in Small Power Plants. Arranged with needle-regulating nozzle hand control, with governor operating deflecting jet. Operates under 584 ft. (178 m.) effective head at 600 r.p.m., developing 300 hp.

rating the needle direct. In addition, there is an auxiliary hand-control, should it be desired. Units of this type are particularly well adapted to small isolated power plants, such as on plantations and for small towns.

In installations where it is not desirable to vary the quantity of water by the governor operating directly on the needle, the jet-deflecting control is used. A medium-sized unit with this type of control is illustrated in Fig. 29. With this unit the setting of the needle is done by hand, the momentary speed control being secured by the governor operating the jet deflector; units of this type ranging in size from 100 horsepower to 1000 horsepower are very satisfactory in service.

An hydro-electric unit of medium size and involving the most advanced construction is illustrated in Fig. 30. In this unit it will be noted that the speed governor is incorporated within the nozzle construction, and the unit is further equipped with the needle-control auxiliary relief type of nozzle. The unit is arranged with two main bearings, the revolving element of the

generator being placed between the bearings, the water wheel being mounted on one end of the shaft and the fly-wheel on the other. The entire unit is mounted on a combined heavy cast-iron base, securing thereby a most rigid construction. This unit involves all of the improvements of the highest grade large power units.

In the medium and larger sized units, cast-iron base plates are neither necessary nor desirable, owing to the very heavy first cost and weight; and furthermore, as in all large units, it is necessary to depend upon the stability of the foundation construction. In units of this type, the combined shaft which carries the water wheel and the revolving elements of the generator and the bearings are furnished by the builder of the water wheels. An example of this type of construction is illustrated in Fig. 31. The wheel runner is of the disc construction and is bolted against a

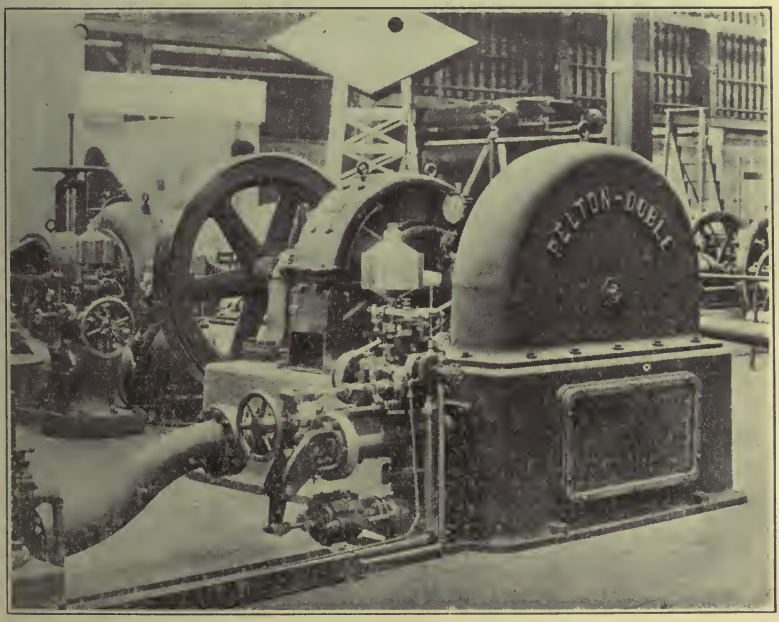


Fig. 30. Ideal Type of Small Horizontal-shaft Single-overhung Hydro-electric Unit Arranged with Needle-regulating Auxiliary-relief Nozzle with Direct Governor Control. Operates under 300 ft. (91.5 m.) effective head at 300 r.p.m., developing 100 hp.

flange forged solid with the water-wheel generator shaft. The bearings are arranged to be mounted on substantial cast-iron base plates, which are bedded directly into the concrete foundations. This type of construction is preferable on all medium and large sized units.

A single-overhung hydro-electric unit of the most modern construction and of large power output is illustrated in Fig. 12. This represents an hydraulic prime-mover now under construc-

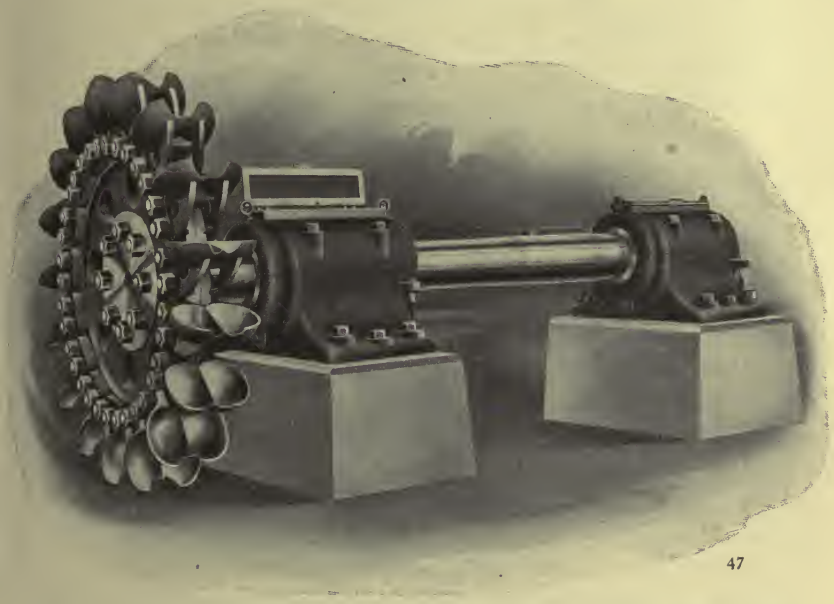


Fig. 31. Single Overhung Horizontal-shaft Construction. Wheel operates under 1200 ft. (366 m.) effective head at 600 r.p.m., developing 1400 hp.

tion, and has embodied in it all of the most recent developments and improvements in the art. In this prime-mover a single jet of water is applied to the buckets of a single wheel, the wheel being mounted on the extreme end of the combined water-wheel generator shaft and being of disc construction bolted directly against the flange forged solid with the hollow chrome-nickel steel oil-tempered shaft. The wheel construction shown in this drawing is of the double-lug type, for the reason that the head of water under which it is to operate, namely, 1650 ft. (500 m.) effective head—with a turning speed of 300 revolutions per min-

ute—secures a favorable ratio between the diameter of the power jet and the pitch diameter of the wheel, so that a thoroughly stable construction could be secured with this type of bucket construction. Were the power output of the wheel larger, it would have required the chain-type or triple-lug construction.

It will be observed that the servo-motor controlling the power output and speed of the unit is carried directly on the power nozzle, the piston of the servo-motor being mounted directly on the extended stem of the power needle; the pendulum head and speed sensitive element with the controlling elements are mounted on the main nozzle body. This unit is arranged to take pressure oil for operating the governor from an independent oil-pressure pumping system.

In addition to the control by the speed sensitive element of the governor, should it be necessary or desirable at any time to control the power output and speed by hand-regulation, it will be observed that a small valve with return mechanism is mounted directly above the servo-motor of the governor. This valve is so constructed with a hand lever that the control of the unit from governor-control to hand-control can be instantly changed by a single movement of the lever operating a four-way valve. On the top of this four-way valve, the hand-control valve is mounted, and is so constructed that by rotating the hand-control wheel, through the means of the floating lever, a corresponding setting of the needle is secured. In other words, if it is desired to carry a half load on this generator, the hand control valve can be set for half position. The power needle will automatically come to this point, and will be maintained at this position until re-set, through the means of the floating lever connections.

A further device installed in the governor of this unit is a load-limiting device, so as to meet the conditions of operations of the power plant, the maximum amount of load which the unit can carry being thus limited. This is of particular importance during seasons of water shortage when it is not desired to have the prime-mover take an excess quantity of water. The arrangement of the auxiliary relief control is secured through the levers as shown in the drawing. The water supplied to this unit is controlled by a single-disc gate valve operated by a reversible water

motor with needle nozzle control. The construction of the centrifugal water disc and collar to prevent the escape of splash water from the housing, is also illustrated. At the extreme end of the shaft is located the spray nozzle for introducing cooling water through the hollow shaft, this cooling water being drawn through the shaft by the vacuum in the wheel housing and discharged into the tail-race.

A further improvement incorporated in this unit, and which has proven to be of great advantage in units located in hot countries, is the arrangement of the tail-race ventilator. This device is so arranged as to take advantage of the partial vacuum that exists in the wheel pit due to the action of the wheel as a blower and the ejector action of the nozzle. Due to this device, the hot air is drawn out of the generator pit and discharged through the tail-race. This type of unit is ideal in every way, and is the preferable one to use wherever the conditions permit of its installation. A number of units of this type of approximately 10,000 horsepower each have been installed, and have proven to be thoroughly satisfactory under the severe conditions of regular operation. The principal advantages of this type are the highest possible efficiency, the simplest form of construction, with the least number of working parts to take care of, while the manner of carrying the shaft gives assurance against the bearings wearing out of line and causing trouble. This type is particularly favorable in the total overall cost of the installed equipment, as it simplifies the pipe fittings and connections, reduces the cost of foundation construction and requires only a single tail-race.

Where the single-overhung type can not be constructed with the power output and speed desired with the available water pressure, the double-overhung type is used; this differs from the single-overhung type in mounting a wheel on both overhanging ends of the combined generator and water-wheel shaft.

The double-overhung type of unit is likewise arranged with two bearings, the revolving element of the generator being mounted between the bearings. A single shaft is used, the rotor of the generator being located between the bearings, with a wheel mounted on each end of the shaft overhanging the bearings. Each wheel is driven by a single jet of water. In the largest

units it would consist of a design similar to that shown in Fig. 12, with a second wheel mounted on the opposite end of the shaft.

With the double-overhung type it is possible to make a prime-mover of double the power output, maintaining the same speed of rotation, with the same conditions of water pressure. Where the double-overhung type is used with automatic water-economizing nozzles, it is preferable to mount a separate governor on each nozzle, and in this way eliminate all long governor rock-shafts and connections. The double-overhung type of prime-mover has been installed in a large number of the most important plants, with units ranging in capacity of from 12,000 to 20,000 horsepower.

In those installations where the head of water available is low, as compared with the quantity of water, and where it is desired to maintain a comparatively high speed of rotation, multiple-jet horizontal-shaft type units have been constructed, and under such conditions are thoroughly satisfactory. In this type,

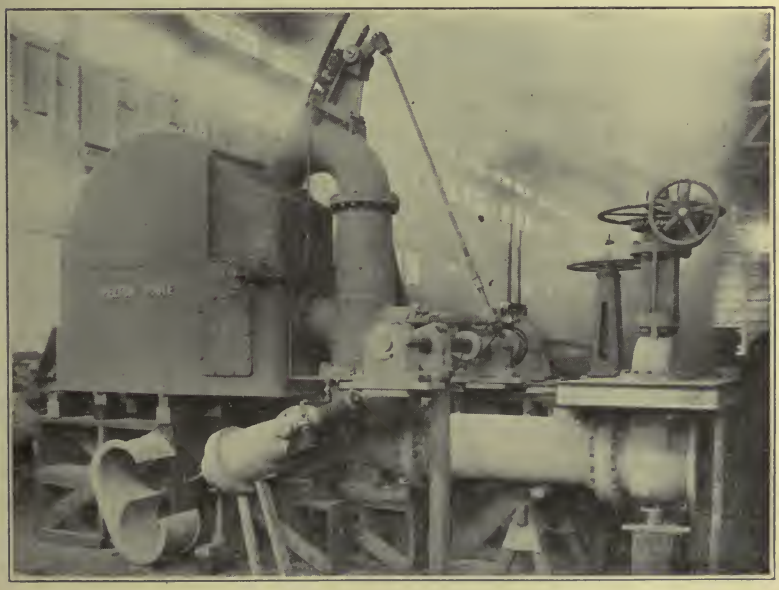


Fig. 32. Horizontal-type Single-overhung Double-jet Wheel with Auxiliary-relief Nozzle, and "Ensign" Vortex Baffle Plate. This wheel operates under 490 ft. (150 m.) effective head at a speed of 300 r.p.m., developing 1900 hp.

usually two jets of water are applied to each wheel from the same nozzle body, the jets being approximately 90 degrees apart. This type has been successfully developed with a single-overhung horizontal-shaft unit, with two jets on a single wheel, a unit of this type being illustrated in Fig. 32. In this unit the power output and speed regulation is controlled by the governor operating the needles. An auxiliary relief nozzle is shown attached to one side, discharging against an "Ensign" vortex baffle plate to take up the energy in the jet from the relief nozzle.

Where a single-overhung double-jet unit will not give the power at the desired speed under the conditions of water pressure at the plant, a double-overhung horizontal-shaft type with two jets on each wheel, making four jets in all on the unit, has been developed. In this type the needles controlling the jets to the two wheels are controlled from a central governor through a rockshaft extending across the back of the unit. On each end of this rockshaft a lever is mounted which operates the auxiliary relief nozzle. For larger power units than that illustrated in Fig. 32, a number of very successful units have been built, of from 11,000 to 15,000 horsepower each, using two wheels on each side of the generator, making four wheels per unit; and each wheel is driven by two jets, thus making eight jets in all. This type is especially well adapted where the water is of such character as to be unsuitable for the pressure type of turbines. Furthermore, owing to the high efficiency of the unit, and especially due to the flat efficiency curve, it is much more favorable for overall twenty-four-hour water economy than turbines. In units of this type four bearings are used, the rotor of the generator being mounted between the two main bearings, and at each end of the unit an outboard bearing is provided, the two water wheels being located on the shaft between one main bearing and one outboard bearing. A unit of this type is illustrated in Fig. 33; and Fig. 34 is a 15,000 horsepower unit similar to the one illustrated in Fig. 33, which represents a unit of 10,500 horsepower.

General practice with Pelton hydraulic prime-movers has been to use the horizontal type, as it usually represents the most favorable first cost when taking into consideration the total cost of the plant, including the foundations. It further has the ad-

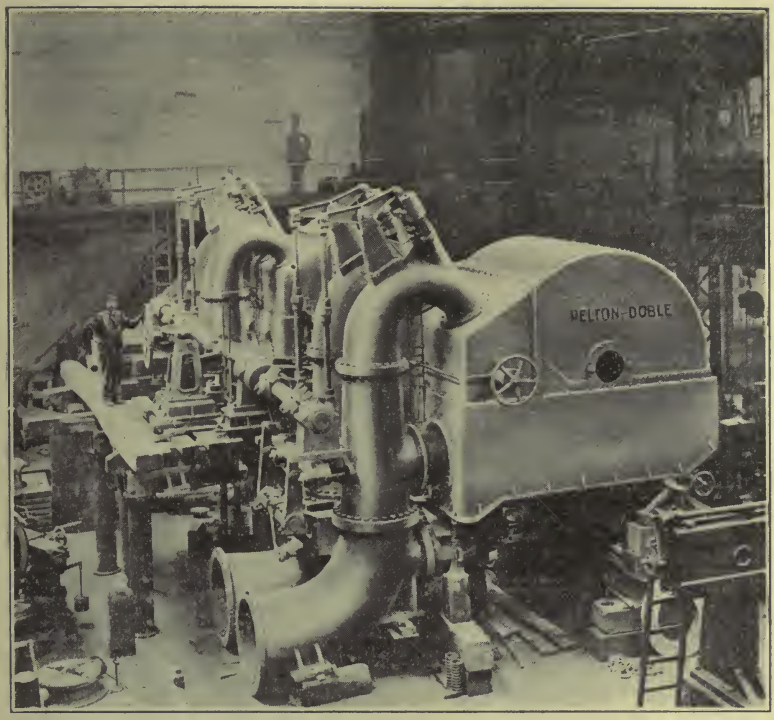


Fig. 34. One of Four 15,000-hp. Units, Horizontal-shaft Type with Four Wheels and Two Jets to Each Wheel. Arranged with auxiliary-relief-control nozzles, operating under 380 ft. (116 m.) effective head at 200 r.p.m.

vantage of simplicity of construction and arrangement of parts available for inspection, lubrication and cleaning. Under certain conditions, however, vertical-shaft types of Pelton hydraulic prime-movers have been installed with excellent results and favorable first cost. This type is especially suitable for comparatively low head plants, where the water contains large quantities of sand, grit or salt and where pressure-type turbines could not be successfully operated. These vertical-shaft units are usually arranged with a wheel runner mounted on the lower end of the vertical shaft, the entire weight of the generator and the wheel runner being carried on a single thrust bearing, the shaft being further provided with vertical guide bearings. With prime-movers of this type, six jets can be installed on a single-wheel

runner. Thus developing under a low head a comparatively large power output from a single wheel, and at a favorable speed of rotation.

A modern plant is illustrated in Fig. 35, this being an interior of the Crane Valley No. 1 Plant of the San Joaquin Electric Light & Power Company. These units are 6000 horsepower each, and operate under 1360 ft. (415 m.) head at 400 revolutions per minute. Four units are installed in the plant. These units

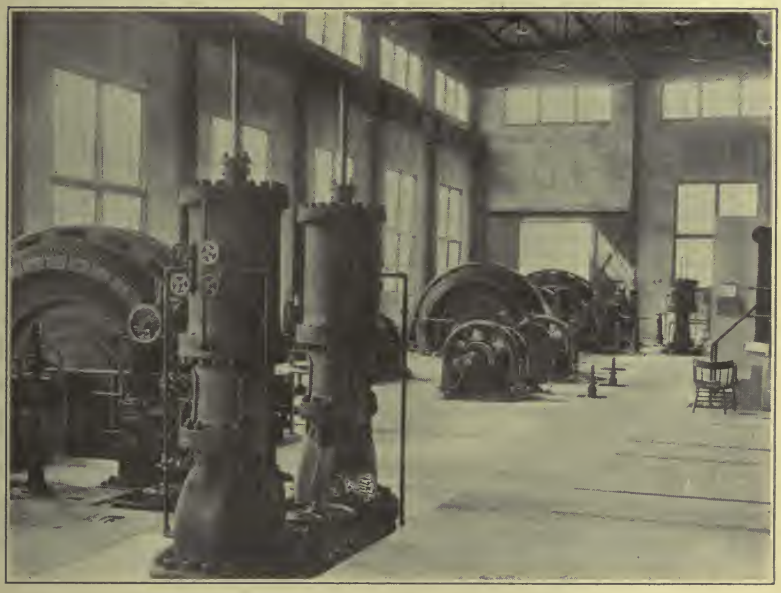


Fig. 35. Interior of the Crane Valley No. 1 Plant of the San Joaquin Light & Power Company, Containing Four 6000-hp. Units. Operates under 1360 ft. (415 m.) effective head at 400 r.p.m., developing 6100 hp. Power output and speed control being taken care of by needle-regulating auxiliary-relief-control nozzles.

are equipped with the auxiliary relief-control nozzles. It will be observed that the gate valves are operated by hydraulic cylinders. These units are of the two-bearing single-overhung type. After this plant was completed a very careful efficiency test was conducted by J. G. White & Company. Figure 36 shows the efficiencies secured on this test. This represents a characteristic efficiency curve from a Pelton wheel.

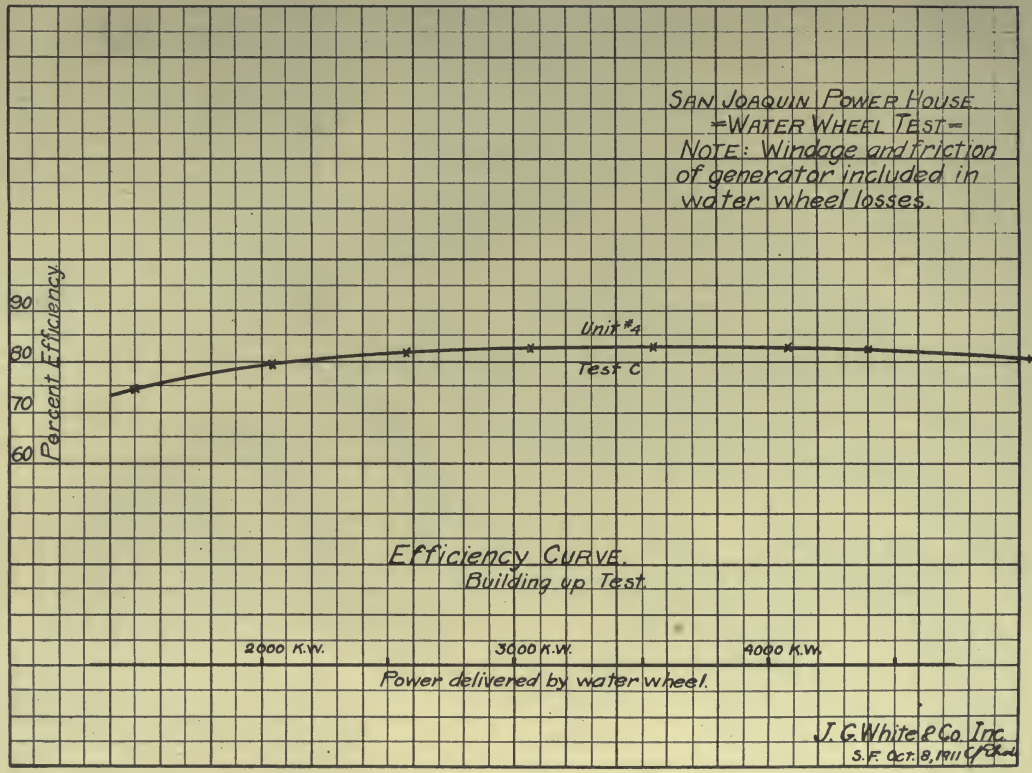


Fig. 36. Efficiency Curves of the 6000-hp. Unit in Crane Valley No. 1 Plant Illustrated in Fig. 35. In conducting these tests, as there was no convenient means of segregating the losses of the generator due to windage and friction, these losses are included in the wheel losses shown by the efficiency curve.

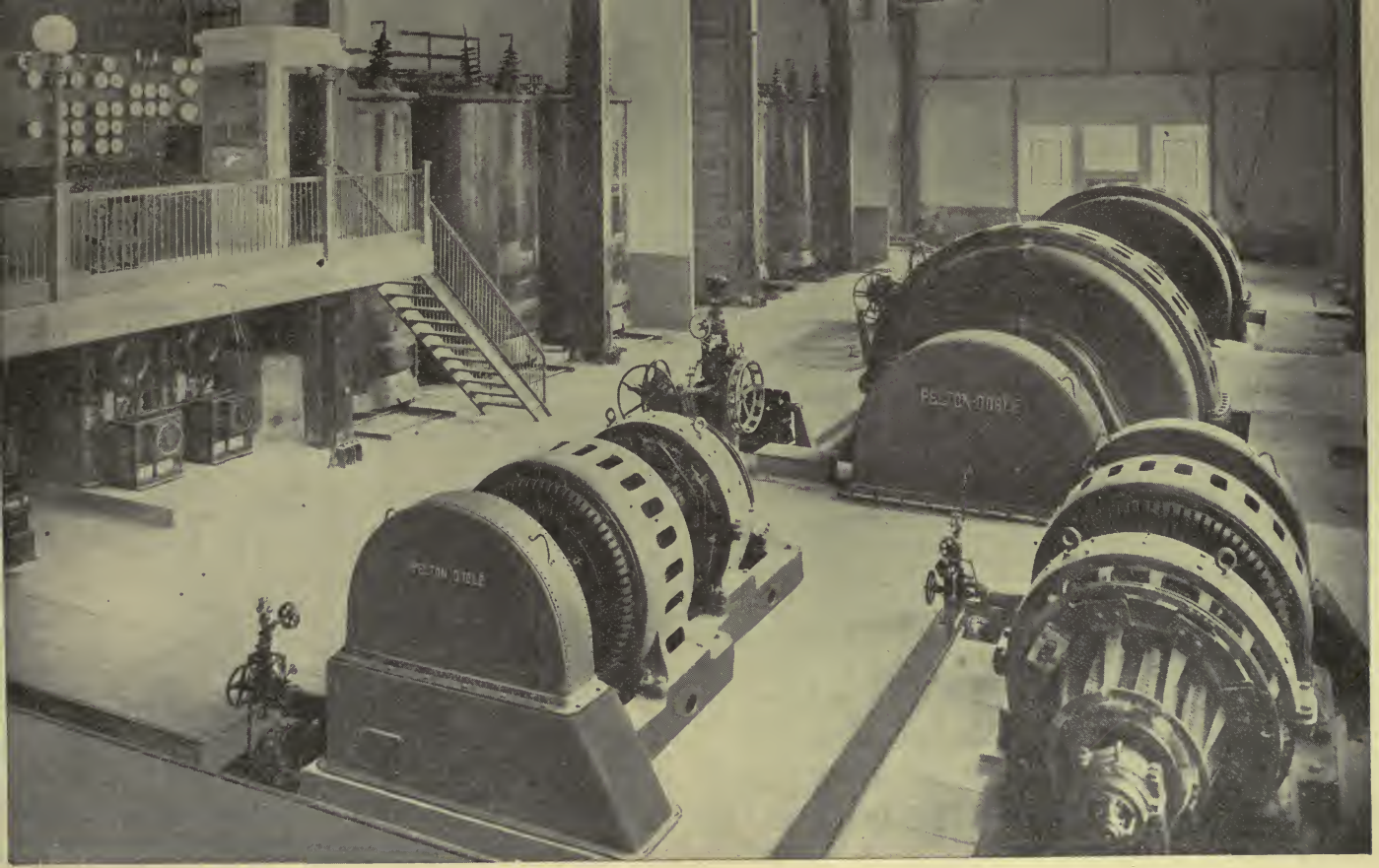


Fig. 37. Drum Power Plant of the Pacific Gas and Electric Company, Showing Two Main Units, and Two Exciter Units and Switchboard Gallery. Two additional units will be installed in 1916. Each unit develops 20,000 hp. under 1330 ft. (405 m.) effective head at 360 r.p.m.

In conducting this test, as it was only possible to segregate the actual electrical losses, and as there were no means for segregating the windage and friction of the generator, these latter losses are included in the efficiency curve.

The most recent plant is the Drum Power Plant of the Pacific Gas and Electric Company, this being illustrated in Fig. 37. In this plant are at present installed two hydro-electric units, double-overhung type, of 20,000 horsepower output each, operating under 1330 ft. (445 m.) head at 360 revolutions per minute. The wheels are of the chain-type construction illustrated in Fig. 4. This plant is equipped with needle-regulating deflecting nozzles, the regulating needles being equipped with remote electric-motor control from the switchboard.

The reason for adopting the needle-regulating deflecting nozzles in this plant was due to the fact that six power plants in series will be installed, taking water from the same source of supply. As there were not available sites in the canyon through which the water canal is carried to install regulating reservoirs, it was necessary to arrange a system of control which would permit of flow of water to the lower plants without momentary interruption. When this plant is completed, it will include four 20,000 horsepower units.

An illustration of the adaptation of the Pelton wheel to a modern mining plant is illustrated in Fig. 38, which shows the interior view of the power plant of the Granby Consolidated Mining, Smelting & Power Company, Anyox, B. C. In this plant Pelton wheels are connected to a large piston blowing-engine, a large piston air-compressor, to three rotary air-blowers of the Connersville type, and also to the electric generators and exciters for the electrolytic process.

It has been the intent of this paper to submit briefly to the interested engineer the principal types of prime-movers that have been developed, with their methods of regulation, and only those types have been described and illustrated which have proven thoroughly reliable and satisfactory under the severe conditions of regular service operation. The art is one that is constantly developing. The limitations as to power output and speed have not as yet been reached and are only limited by the

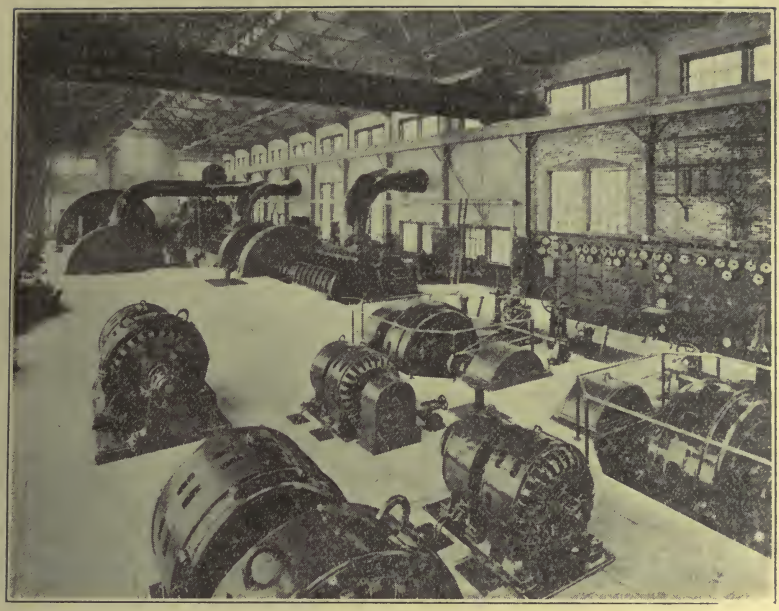


Fig. 38. Interior of a Modern Mining Plant, the Granby Consolidated Mining, Smelting & Power Company, Anyox, B. C.

The plant consists of three water wheels connected to rotary air blowers of the Connersville type, each wheel developing 775 hp. under 374 ft. (114 m.) effective head, at 115 r.p.m.

Two water-wheel generator units, each wheel developing 1400 hp. under 370 ft. (113 m.) effective head at 400 r.p.m.

One water wheel for motor-generator set, developing 75 hp. under 370 ft. (113 m.) effective head, at 900 r.p.m.

One water wheel for Connersville blowing engine, developing 1400 hp. under 374 ft. (114 m.) effective head at 75 r.p.m.

One water wheel for Nordberg air compressor, wheel developing 800 hp. under 374 ft. (114 m.) effective head at 84 r.p.m.

necessities of the particular installation. As to the limits of capacity, they are restricted only by the profitable demand for the power and by the quantity and head of water available; the only practical limitations as to the head or pressure under which a power plant can be constructed, is the cost of the pressure pipe line.

Plans have been developed which demonstrate that an hydraulic prime-mover, thoroughly satisfactory from the standpoint of first cost, upkeep and reliable operation, can be constructed for heads in excess of 6000 ft. in a single drop, and in

units as large as 30,000 horsepower each, the limitations being the question of the cost and the difficulties of securing a satisfactory pressure pipe line, an available source of water supply which can be developed at a reasonable cost, and a satisfactory market for the power generated. Other than this, the results to be secured from units of this capacity and operating under these conditions would be absolutely satisfactory in regular operating service. It is not predicted that this represents the limit of capacity or head. It would indicate, however, the approach to a limit, as representing possibly the maximum conditions of a reliable water supply that can be secured within a reasonable cost of development and within a reasonable distance of a profitable market.

The several illustrations which have been introduced in this paper have been selected from regular shop photographic record prints as being the best means of illustrating the general development of the art and improvements in the details of construction and in the systems of regulation, and from this standpoint will be of interest to engineers.

The efficiency to be secured from an Impulse Prime-Mover is affected by the type of the unit, the head or pressure that it is to operate under, and the speed of rotation; these factors determining the ratio of the jet and the pitch diameter of the wheel.

A characteristic efficiency curve, showing the results from a medium sized prime-mover under actual operating conditions, is shown in the efficiency curve of the Crane Valley No. 1 Power Plant, Fig. 36.

Under exceptionally favorable conditions the efficiency of a Pelton hydraulic prime-mover will range between 83% and 86%, depending upon the special limitations of the installation. It is anticipated that these extremely favorable efficiencies will be somewhat improved, and with heads in excess of 3000 ft. with large sized power units, it is reasonable to predict an efficiency of approximately 90%.

In considering these questions of efficiency, it must be appreciated that they are based upon the prime-movers installed in actual operating plants and on the basis of regular commercial service, and represent the total overall efficiency of the prime-mover.

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